

# Astrophysics Science Division

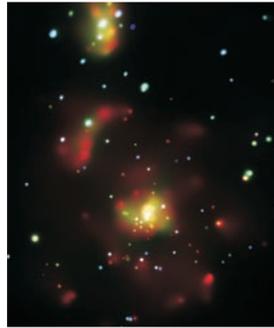
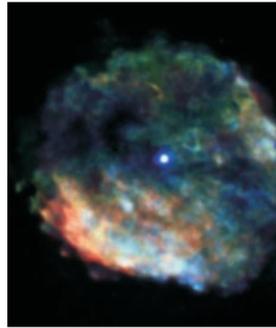
NASA Goddard Space Flight Center



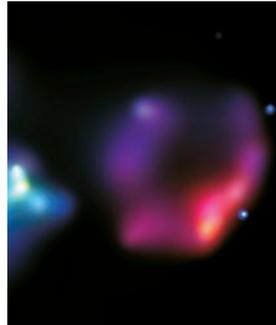
Observational Cosmology

ExoPlanets and Stellar Astrophysics

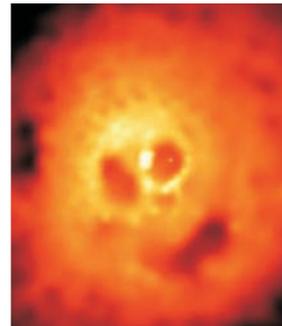
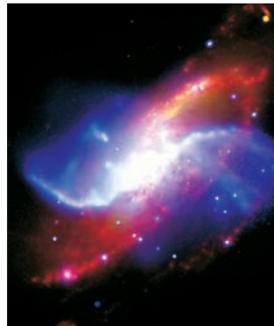
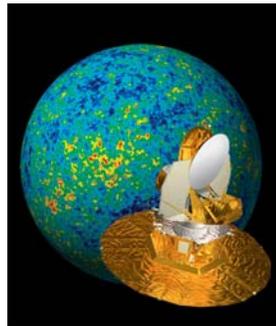
Gravitational Astrophysics



X-ray Astrophysics



Astroparticle Physics



Observational Cosmology

ExoPlanets and Stellar Astrophysics

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## Introduction

The Astrophysics Science Division (ASD) at Goddard Space Flight Center (GSFC) is one of the largest and most diverse astrophysical organizations in the world, with activities spanning a broad range of topics in theory, observation, and mission and technology development. Scientific research is carried out over the entire electromagnetic spectrum—from gamma rays to radio wavelengths—as well as particle physics and gravitational radiation. Members of ASD also provide the scientific operations for three orbiting astrophysics missions—WMAP, RXTE, and Swift, as well as the Science Support Center for the Fermi Gamma-ray Space Telescope. A number of key technologies for future missions are also under development in the Division, including X-ray mirrors, and new detectors operating at gamma-ray, X-ray, ultraviolet, infrared, and radio wavelengths.

ASD has a strong suborbital research program, with four balloon programs and three sounding rocket programs at present. The Division also supports research in the astronomical community through the High Energy Astrophysics Science Archive Research Center (HEASARC), which now also contains Cosmic Microwave Background data, as well as support services for observers using the Fermi, Suzaku, Integral, XMM-Newton, GALEX, RXTE, WMAP, and Swift missions. Finally, ASD has a strong Education and Public Outreach program, to convey the exciting discoveries from NASA missions to school teachers, students, and the public.

ASD staff includes 365 people, most of whom are scientists and engineers, along with a support staff of software programmers, resource analysts, and administrative personnel. There are about 80 civil servant scientists, and a much larger number of contractor and university-based scientists. Several dozen postdoctoral fellows and graduate students are also in residence.

Organizationally, ASD comprises five laboratories: the Astroparticle Physics Lab (code 661; Neil Gehrels, chief); the X-ray Astrophysics Lab (662; Rob Petre, chief); the Gravitational Astrophysics Lab (663; Joan Centrella, chief); the Observational Cosmology Lab (665; Jonathan Gardner, chief); and the Exoplanets and Stellar Astrophysics Lab (667; Jennifer Wiseman, chief). Alan Smale heads the High Energy Astrophysics Science Archive & Research Center (HEASARC) Office, Phil Newman heads the Office of Scientific Computing, and Felicia Jones-Selden leads the Instrument Development Group. Division management includes William Oegerle (Director), Felicia Jones-Selden (Deputy), Curtis Odell (Assistant), Kim Weaver (Associate for Science) and Harley Thronson (Associate for Advanced Concepts).

The overriding goals of ASD are to carry out cutting-edge scientific research, provide Project Scientist support for spaceflight missions, implement the goals of the NASA Strategic Plan, serve and support the astronomical community, and enable future missions by conceiving new concepts and inventing new technologies.

William Oegerle  
Director, Astrophysics Science Division  
NASA Goddard Space Flight Center



## I. 2008: Year in Review

The past year has been an eventful one for the ASD. Summarizing all of the noteworthy events during the year is a daunting task, much like describing the tip of an iceberg. There is much, much more below the surface, and the remainder of this document provides a broader and deeper view into ASD's activities. However, even this whole document only describes a portion of the Division's work. With that caveat in mind, here is 2008 in review.

The year began with a bang as the BESS-Polar II Antarctic balloon flight completed a successful 24.5-day flight, collecting an enormous amount of data on the spectra of cosmic-ray anti-protons. The data is still being analyzed and we look forward to the results soon. At the same time, the CREAM balloon payload (co-investigators Barbier, Mitchell) was also in flight above the Antarctic. Its goal is to measure the high-energy cosmic-ray spectrum.

While BESS was circumnavigating the South Pole, Neil Gehrels was delivering his Rossi Prize lecture "Gamma-ray Burst Discoveries with the Swift Mission" at the 211th AAS meeting in Austin, Texas, on behalf of the Swift team and himself (joint winners). It was a banner year for Neil, as he was inducted into the American Academy of Arts & Sciences in the Spring of 2008, and then was awarded the Henry Draper medal by the National Academy of Sciences in early 2009. Other significant awards during the year include the Lindsay Award to John Baker and Joan Centrella for their work on the modeling of black hole mergers and the subsequent gravitational wave signatures, and the AAS Weber Prize to Pete Serlemitsos for his achievements in inventing new instrumentation for X-ray astronomy.

Also in January 2008, the ASD team of Barry, Danchi and Kuchner announced the first results from the Keck Observatory Nulling instrument. As one of the first teams selected for Shared Risk science, they were observing at the Keck Observatory when the recurrent nova RS Oph erupted. The nuller observations provided interesting information on the evolution of the nova (described further in the Research section).

News about ASD missions and scientists frequently reach the public. On average, the division issues about between two and three releases and/or Web portal features each month.

In 2008, three stories merited NASA media teleconferences: the Hubble Space Telescope's first-ever visible-light observation of a planet around the nearby star Fomalhaut; the first all-sky image from the newly launched Fermi Gamma-ray Space Telescope; and the study of a gamma-ray burst so bright it could have been seen with the unaided eye — even though it occurred more than 7 billion light-years away.

Other stories receiving significant media coverage include:

- Fermi's discovery of gamma-ray-only pulsars;
- From Swift, the discovery of an X-ray pulse that signaled the first moments of a supernova explosion, as well as the detection of the farthest-known gamma-ray burst (12.8 billion light-years away);
- And a mysterious extragalactic radio background uncovered by a balloon-borne experiment named ARCADE.

In Spring 2008, the X-ray Quantum Calorimeter (XQC) payload had a successful sounding rocket flight from White Sands, as described by Porter elsewhere here. This payload employs X-ray microcalorimeters developed at GSFC to study the diffuse soft-X-ray sky. This is a joint program with the University of Wisconsin (McCammon, PI; Porter, GSFC lead co-I).

The NASA Senior Review of Operating Missions was released in April 2008, with a few pleasant and also unpleasant surprises. ASD is involved in 7 out of the 10 missions reviewed. On the pleasant side, Swift was rated the #1 mission in terms of science per dollar (the metric used), ahead of flagship mission Chandra, and was recommended for a funding augmentation. Also, the Suzaku mission was rated #4 (behind Swift, Chandra and GALEX). ASD provided mirrors for the Suzaku telescope, a soft-X-ray spectrometer (not currently operating), and runs the U.S. Guest Investigator program and distributes Suzaku data to the U.S. through the HEASARC archive. With budgets tight, it was recommended that US Guest Observer programs be eliminated for XMM and Integral by FY10,

and that RXTE operations cease in February 2009. XMM and Integral are ESA missions and will continue to operate, and they will be reconsidered at the next Senior Review, where U.S. funding could potentially be restored. RXTE will continue to operate on a shoestring until it can also be reviewed again in FY10. In June, the results of the Senior Review of NASA Archives were announced, and HEASARC ranked second place, in a tie with MAST and NED and behind the very cost-effective ADS. Full in-guide funding was recommended for HEASARC.

On June 11, 2008, the Gamma Ray Large Area Space Telescope (GLAST) was successfully launched from the Cape, and renamed the Fermi Gamma-ray Space Telescope. A number of ASD scientists were deeply involved in the development of the Large Area Telescope (LAT) and its Anti-Coincidence Detector (ACD). The ACD was built at GSFC. After launch, GSFC also provides the Science Support Center for Fermi. Hats off to Steve Ritz (Fermi Project Scientist), Julie McEnery (Deputy), Neil Gehrels (Deputy), Alex Moiseev and Dave Thompson (ACD), Jerry Bonnell, David Band, Robin Corbet, Dave Davis, Masa Hirayama, and Bob Hartman (now Emeritus). The observatory is operating extremely well, and there were a number of early science results presented at the January 2009 AAS meeting, including the discovery a new class of pulsars that are only observable in gamma-rays. The Fermi collaboration released its LAT Bright Source List the first week of February 2009. This is the first public release of new sources detected by the observatory.

In Spring 2008, we received the good news that one of our Small Explorer (SMEX) proposals, the “Gravity and Extreme Magnetism SMEX” (GEMS), was selected for a Phase A study. GEMS is a mission dedicated to the study of black holes and other energetic phenomena through X-ray polarization, and is described in further detail later in this document. The Phase A report was submitted in December 2008, and a site visit is scheduled for April 2009, with selection a month or two later. If selected, this mission would open up a new research area in X-ray astrophysics. The Soft X-ray Spectrometer (SXS; Rich Kelley, PI) was also selected as a Mission of Opportunity instrument to fly on JAXA’s Astro-H mission in 2013. This spectrometer uses a microcalorimeter with a resolution of about 1000 (4 eV), and was developed at GSFC.

The James Webb Space Telescope (JWST) was confirmed in July 2008 to enter into Phase C (the construction phase). This milestone was achieved after more than a decade of work by many folks at Goddard, including our JWST Project Scientists: John Mather, Jon Gardner, Mark Clampin, Matt Greenhouse, Bernie Rauscher, Chuck Bowers and George Sonneborn. Harvey Moseley is the PI for the microshutters, which will be delivered to ESA in Spring 2009, to provide a multi-object spectrograph capability for the NIRSpec instrument.

In Fall 2008, NASA HQ announced that the Joint Dark Energy Mission (JDEM) would not be competed. Instead, a JDEM Project Office was established at GSFC with the role of leading the mission development, in concert with DOE. JDEM science teams will be solicited through an Announcement of Opportunity in Spring 2009. A Science Coordination Group (chaired by Neil Gehrels) was formed, largely from the original JDEM concept study teams, and was tasked with working with the GSFC Project office to agree on a Reference Mission design. Several ASD scientists (Moseley, Hinshaw, Benford) are deeply involved in these activities.

The phrase “All good things come to those who wait” was surely penned for the team waiting to carry out Servicing Mission 4 (SM4) on Hubble Space Telescope. SM4 was cancelled after the Columbia orbiter failure in 2003, and was resurrected by NASA Administrator Griffin in 2006. After a delay to Fall 2008, SM4 was once again delayed by an onboard failure of the Science Data Formatter only weeks before the mission. With SM4 launch now slated for May 12, 2009, we look forward to finally installing Wide Field Camera 3 (Randy Kimble, lead NASA instrument scientist), the Cosmic Origins Spectrograph and the repair of STIS (Woodgate, PI) and ACS instruments.

In 2009, we look forward to supporting the National Academy’s Astro2010 Decadal Survey of Astronomy & Astrophysics, successful completion of HST/SM4, selection of the next Small Explorer, continuing development for of instruments and hardware for NuStar, Asto-H and SOFIA, support of JDEM, and the initial flight of the Proto-EXIST (balloon).

## II. Awards

In the last few years, a number of scientists in the Astrophysics Science Division (ASD) were singled out for extraordinary contributions to their respective fields.



John Mather

The most prestigious honor bestowed on an ASD scientist is the 2006 Nobel Prize for Physics, which was awarded jointly to Goddard's John Mather and George Smoot of the University of California "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation" using

NASA's Cosmic Background Explorer (COBE) satellite, which launched in 1989. Mather joined Goddard as Project Scientist for the COBE mission, and his Nobel medal is now on display in the Building 8 lobby. He currently serves as Senior Project Scientist for the James Webb Space Telescope and is a Senior Astrophysicist in ASD's Observational Cosmology Laboratory.

**Since 2006, ASD scientists have been recognized with numerous honors, including a Nobel Prize in Physics.**

In January 2009, two ASD scientists were recognized. Peter Serlemitsos of the X-ray Astrophysics Laboratory was awarded the American Astronomical Society's Joseph Weber Award for Astronomical Instrumentation. The award recognizes the design, invention or significant improvement of instrumentation leading to advances in astronomy. The contributions of Serlemitsos led to major advances in both X-ray optics and multiwire proportional counters. These advances enabled many ground-breaking missions, including OSO-8, HEAO-1, RXTE, BBXRT, ASCA, Suzaku, as



Peter Serlemitsos



Neil Gehrels

well as the upcoming Astro-H mission.

In the same month, Neil Gehrels, who heads the Astroparticle Physics Laboratory, was awarded the 2009 Henry Draper medal by the National Academy of Sciences. The citation reads: "For his pioneering contributions to gamma-ray astronomy. His leadership of the Compton Gamma Ray Observatory and the Swift Mission has led to new insights into the extreme physics of active galactic nuclei and gamma ray bursts." The National Academy of Science only presents this award every four years. In 2005, the Academy recognized Charles Bennett, another Goddard scientist, for his leadership of the WMAP mission. So, Goddard scientists have been awarded the last two Draper medals.

In March 2008, the 228th Class of Fellows of the American Academy of Arts and Science included Gehrels. The American Academy, founded in 1780 by John Adams, honors distinguished scientists and leaders in public affairs, business, administration, and the arts. Gehrels was inducted into the same class as filmmakers Joel and Ethan Coen, artist Richard Tuttle, soprano Dawn Upshaw and blues legend B. B. King.

Last May, Joan Centrella, chief of the Gravitational Astrophysics Laboratory, and John Baker, an astrophysicist with the Numerical Relativistic Astrophysics Group, shared the John C. Lindsay Memorial Award for Space Science. Their groundbreaking computer simulations show what happens when two supermassive black holes collide and merge. This award recognizes the Goddard employee who best exhibits broad scientific accomplishments in the area of space science.



Joan Centrella



John Baker

In 2007, Gehrels and the team for NASA's Swift satellite were awarded the Bruno Rossi Prize from the American Astronomical Society (AAS). This annual award given by the AAS High Energy Astrophysics Division recognizes significant contributions in high-energy astrophysics.

Later that year, the AAS awarded Harvey Moseley the Joseph Weber Award for instrumentation in recognition of his extraordinary contributions—spanning two decades—to the development of astronomical detectors covering wavelengths from X-rays to the submillimeter. These detectors have been used in some of NASA's most successful space missions, from the Cosmic Background Explorer (COBE) to the infrared space observatory Spitzer, that have profoundly changed our understanding of the universe. Moseley continues to focus his creative energies on the development of the microshutter array, a micromechanical device which will allow the James Webb Space Telescope to make its most critical observations 100 times faster.



Harvey Moseley

*On the Web*

ASD press archive  
[astrophysics.gsfc.nasa.gov/press/](http://astrophysics.gsfc.nasa.gov/press/)



Ann Hornschemeier

Also in 2007, Ann Hornschemeier won the AAS Annie Jump Cannon Award.

The Cannon Prize is for outstanding research and promise for future research by a post-doctoral woman researcher in North America.



Tod Strohmayer

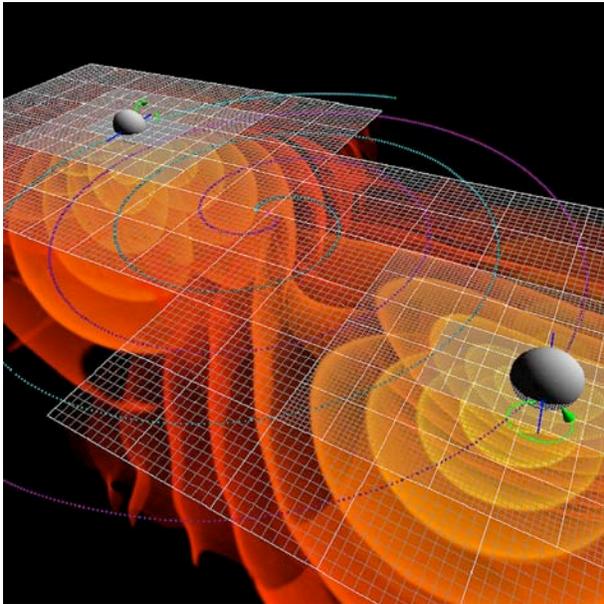
In 2006, ASD's Tod Strohmayer shared with AAS Rossi Prize with MIT's Deepto Chakrabarty and Rudy Wijnands of the University of Amsterdam. Their work, done both independently and sometimes as collaborators, has been described as breakthrough in interpreting the complex signals emitted as X-ray light from millisecond pulsars.

### III. Research

*A few representative research programs in ASD are described below*

#### Gravitational Radiation from Merging Black Holes

The numerical relativistic astrophysics group of the ASD Gravitational Astrophysics Laboratory continues numerical simulation studies of merging binary black hole systems. They are predicted to be among the most energetic astronomical events, releasing energy as much as  $10^{55}$  erg/s in the form of gravitational radiation. Consequently these are among the key target sources for gravitational wave observation. Mergers of stellar-scale systems occur in the sensitivity band of ground-based observatories such as the Laser Interferometer Gravitational Wave Observatory (LIGO). The Laser Interferometer Space Antenna (LISA) will be sensitive to mergers of massive black hole systems ranging from roughly 10 thousand to 10 million solar masses at cosmological distances (to  $z \sim 10$  and be-



Gravitational energy produced in when binary black holes collide can impart a kick to the merged remnant when the radiation is emitted asymmetrically. Simulations suggest that these large kicks could have a dramatic impact on the relation between a merged massive black hole and its host galaxy. Credit: NASA

eyond). These observations form the basis for many of LISA's science goals.

Einstein's theory of General Relativity (GR) allows clear predictions for the physics of these mergers, but a full theoretical understanding of these energetic events and the gravitational-wave signals they produce requires detailed supercomputer simulations integrating the equations of GR. Following major advances in the basic techniques for these simulations in 2005–6, recent work at Goddard has included numerical studies of a variety of configurations of comparable-mass binary systems.

**The description of the merger radiation provided by these numerical simulations will provide a basis for drawing stronger inferences from gravitational wave observations.**

Several of these studies have focused on providing a detailed characterization of the gravitational waveform signals generated in binary black hole mergers. These studies first focused on developing a thorough understanding of the gravitational-wave radiation generated by mergers of non-spinning black hole systems. In collaboration with researchers and the University of Maryland, the Goddard team (Baker, Centrella, Kelly, McWilliams, Thorpe, van Meter) developed an analytic representation of the waveforms that is consistent with the post-Newtonian approximation that applies before GR-effects become too strong, but also provides a close approximation to the numerical results describing the strong radiation generated in the final moments of merger. Currently, the team is working toward a thorough description of a simple class of spinning black hole systems, as well as an extension of the analytic waveform model to describe this broader class of systems.

The description of the merger radiation provided by these numerical simulations, while still incomplete, will provide a basis for drawing stronger inferences from gravitational wave observations. Researchers at Goddard are currently investigating how the merger signal predictions will enhance the precision with

which astronomers will be able to estimate the parameters of merging systems, including sky position and distance, with careful analysis of LISA data.

The large amount of gravitational energy produced in these mergers can lead to a significant back-reaction force on the remnant black hole when the radiation is emitted asymmetrically. Numerical relativity simulations indicated that this “kick” imparted to the merged black hole can be larger than 2,000 km/s in particular cases. Such large kicks would have a dramatic impact on the relation between a merged massive black hole and its host galaxy or proto-galaxy, impacting astronomical expectation beyond gravitational waves. The Goddard team continues to study these kicks with attention to the dependence of the kick on the binary parameters, particularly the ratio of the two black holes’ masses. These results will impact the likelihood of large kicks in generic merging systems.

It is not yet clear what potentially observable effects the strong dynamical gravity of these merging systems could have on any surrounding gas or other matter. The Goddard team has begun investigations tracing the trajectories of particles in the vicinity of the merging black holes, with plans for including more realistic models of possible surrounding gas, as warranted by ongoing preliminary investigations.

### Pulsar High Energy Emission

Modeling and understanding the high-energy pulsed emission from rotation-powered pulsars—and, more recently, magnetars—has been a major endeavor for the last 25 years. In the last several years, Alice Harding and her collaborators have focused on predictions of gamma-ray light curves and phase-resolved spectra, as well as population statistics, for different emission models in preparation for the new pulsar discoveries by the Fermi Gamma-ray Space Telescope. In particular, we have been exploring a model for high-energy emission known as the “slot gap,” where particles are accelerated and radiate from the neutron star surface to near the pulsar’s light cylinder along the edge of the open magnetic field region.

The slot gap model is a consequence of the electron-positron pair cascades that take place near the pulsar polar caps, which we have been studying since the early 1980s. In young pulsars, such pair cascades screen

the accelerating field at low altitude along most field lines. But the decrease in the parallel electric field near the open-field boundary (which is assumed to be fully conducting) prevents pair production in a narrow slot gap, thereby screening the electric field there. Particles therefore can accelerate and radiate at high altitudes.

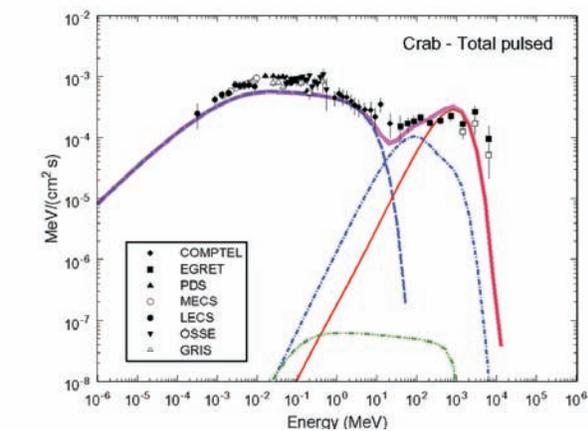
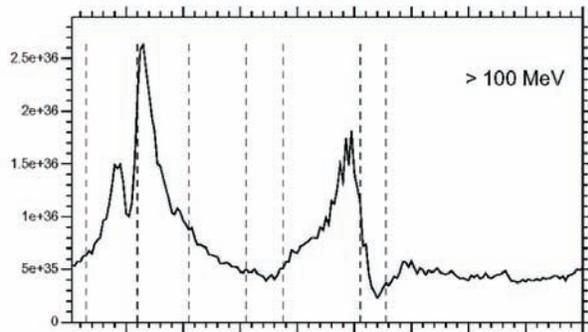
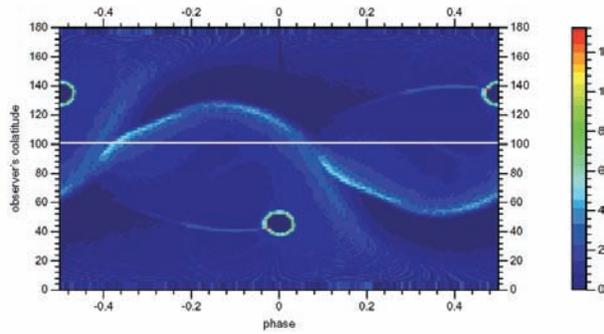
The combination of relativistic aberration and travel-time delays causes all their radiation along the trailing side of the gap to arrive in phase as seen by a non-rotating observer, which forms caustics in the emission pattern. If the observer light-of-sight crosses the caustics from both poles, two sharp peaks are seen in the light curve. The model produces light curves very much like the ones seen from gamma-ray pulsars.

As pulsars age, the slot gap becomes progressively wider, eventually filling the entire open-field region and accelerating particles over a large fraction of the magnetosphere. As slot gaps disappear in older pulsars—many being “recycled” millisecond pulsars, their gamma-ray efficiency increases to 10 percent or more of their spin-down power. Using this model, our population synthesis studies have predicted that Fermi will detect around 150 normal pulsars, with about half of these being radio-loud, and detect about 50 millisecond pulsars, about 12 being radio-loud.

**Our studies have predicted that Fermi will detect around 150 normal pulsars, with about half of these being radio-loud, and detect about 50 millisecond pulsars, about 12 being radio-loud.**

In the six months since its launch (four in nominal sky survey), Fermi has so far discovered gamma-ray pulsations from 18 radio-loud pulsars (including 7 millisecond pulsars) and 14 radio-quiet pulsars. Including Fermi detections of previously known EGRET pulsars brings the total to more than three dozen.

The large number of photons detected from the bright Vela pulsar has enabled Fermi to rule out a super-exponential, high-energy cutoff of its spectrum that we predicted would be a consequence of near-surface pair cascades, thus placing the emission site in the



These graphs illustrate the success of the slot gap model in explaining gamma-ray emission from the Crab pulsar. Top left: Model light curve for photon energies greater than 100 MeV and an observer angle of 100 degrees. Bottom left: Sky intensity map (observer angle vs. rotational phase). Top right: Model phase-averaged spectrum showing pair synchrotron (dashed), primary electron synchrotron (dot-dashed) and primary electron curvature (solid) radiation components.

outer magnetosphere. We are currently modeling the expected light curves of both individual sources and the distributions of light curve characteristics, such as gamma-ray peak separation and phase lag with the

radio pulse, for the whole population using the slot gap and alternative outer-gap models to compare with those of Fermi pulsars. We believe that, with the large number of Fermi pulsars detected over many decades in age and spin-down power, we will be able to finally map the geometry of particle acceleration in pulsar magnetospheres.

### Lab Astrophysics: High Energy Laboratory Astrophysics Using an X-Ray Microcalorimeter with an Electron Beam Ion Trap

Our laboratory astrophysics program is designed to simulate astrophysical plasmas in the laboratory in order to benchmark and provide guidance to the atomic codes that form the basis of the spectral synthesis models used in X-ray astrophysics. These models are used to relate spectra observed from an astrophysical object to conditions in the source, including temperature, ionization-equilibrium, composition, density, turbulence and bulk motion. This work is fundamentally important as X-ray astrophysics begins to use high-resolution spectroscopy as the dominant tool in exploring the physics of X-ray emitting objects.

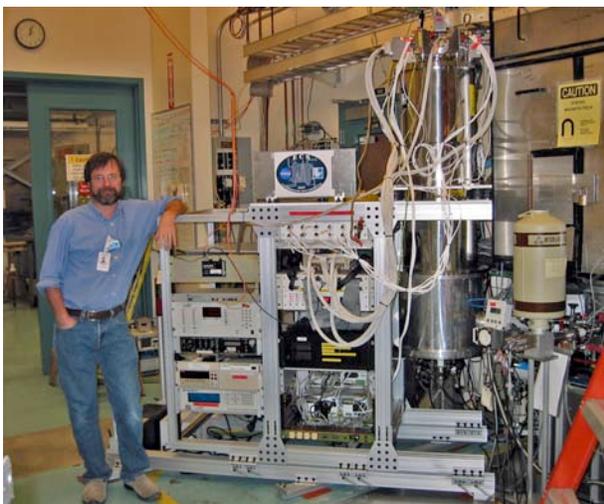
**This system has produced well over two dozen peer-reviewed articles, and it has made critical measurements of absolute cross sections in L-shell Fe and Ni, as well as charge-exchange measurements in S, C, O, and Fe.**

This has already started with the observation of bright point sources with the high-resolution dispersive spectrometers on Chandra and XMM/Newton. It will become critically important with the upcoming Astro-H and International X-ray Observatories, where every observation will produce a detailed, high-spectral-resolution image. Our program is designed to demonstrate and correct the accuracy of the spectral synthesis models in controlled ground-based experiments that will give us confidence that we have correctly ascribed observed spectral features to known conditions in the astrophysical source.

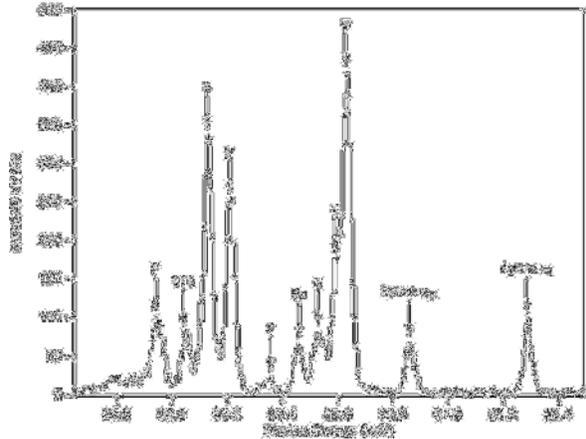
The basis of our program is a high-resolution, non-dispersive, X-ray calorimeter spectrometer, a suite of very-high-resolution dispersive spectrometers, and the Electron Beam Ion Trap (EBIT) plasma generator at the Lawrence Livermore National Laboratory (LLNL). Other collaborating institutions include Stanford University and the National Institute of Standards and Technology. The LLNL EBIT can produce nearly any plasma conditions from low charge states in light elements to bare uranium with electron beam energies of up to 200 keV. Nearly any charge state of any astrophysically interesting element can be produced, either as a pure charge state or in a Maxwellian distribution at known temperature.

Non-equilibrium ionization conditions can also be produced with almost any astrophysically interesting ionization parameter. Typical measurements in our program include spectral-line identification, absolute cross sections, recombination, charge-exchange recombination, and cross sections in thermal and non-thermal distributions. Measurements are related back to theory, the results of atomic calculations, and to the standard X-ray spectral synthesis models used in X-ray astrophysics.

A key instrument in these measurements is a broad-band, high-resolution X-ray calorimeter instrument provided by GSFC beginning in 2000 and now on its third revision. This system has been operated almost



The ECS x-ray calorimeter instrument installed at the Electron Beam Ion Trap Facility at LLNL. Credit: NASA/LLNL



A spectrum of He and H-like Xe taken with the ECS instrument at EBIT using the high-band calorimeters. Credit: NASA/LLNL

continuously for the past 8.5 years. It has produced well over two dozen peer-reviewed articles, and it has made critical measurements of absolute cross sections in L-shell Fe and Ni, as well as charge-exchange measurements in S, C, O, and Fe. Many investigations are on going.

GSFC first installed an X-ray calorimeter instrument at the LLNL EBIT facility in the summer of 2000, based on the engineering-model detector system for the Astro-E observatory. The system was significantly upgraded using technology developed for Astro-E2 in 2003. A dedicated facility-class instrument designed from the ground up for laboratory astrophysics was installed in 2007. The current instrument, dubbed the EBIT Calorimeter Spectrometer (ECS), utilizes a 32-channel X-ray calorimeter array from the Astro-E2 program installed in a long-lifetime, automated laboratory cryostat that enables continuous experiments for up to 70 hours with a two-hour recharge. The detector array is populated with 16 mid-band (0.05-12 keV) X-ray absorbers with 4.5 eV FWHM resolution at 6 keV, and 16 high-band (0.1-100 keV) X-ray absorbers with 30 eV FWHM at 60 keV.

We are currently designing and constructing the fourth-generation instrument that will be based on detector technology from the IXO development program. It will be installed in a completely automated cryogen-free cryostat. The fourth-generation instrument is dubbed the Transition-Edge Microcalorimeter Spectrometer (TEMS) and will be composed of

a checkerboard hybrid of 128 low-band (0.05-1 keV) pixels with 0.8 eV resolution at 1 keV, and 128 mid-band (0.05-10 keV) pixels with 2.0 eV resolution at 6 keV. In addition, there will be a 64 channel high-band array (0.1-200 keV) with 30 eV resolution at 60 keV. The TEMS instrument will become the workhorse instrument in our laboratory astrophysics program to make sure that our measurements and understanding of atomic processes are ready to interpret the spectra we will obtain with the Astro-H and IXO observatories. TEMS will be installed at the EBIT facility in 2010.

### Lab Astrophysics: Optical Properties of Astronomical Silicates with Infrared Techniques (OPASI-T)

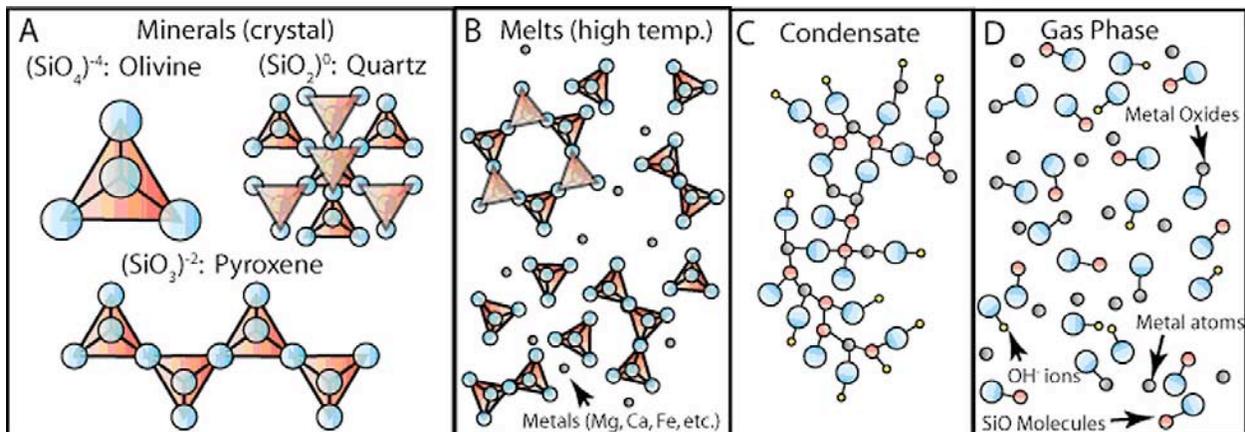
Astronomical dust is ubiquitous. It has been found in our own solar system, around nearby stars with debris disks, in star-formation regions and even in far-distant galaxies. This dust shields sources from our view at optical wavelengths, reprocesses short-wavelength light to longer wavelengths, and provides an environment where planets can form and grow.

The OPASI-T program is designed to directly address two major questions. What are the optical properties of dust grains in the far-infrared, and how do these

properties vary as a function of wavelength, temperature and crystallinity.

**The data obtained through the OPASI-T program is critical for interpretation of astronomical spectra obtained at long wavelengths.**

Stephen Rinehart and collaborators will conduct a series of laboratory experiments designed to answer these questions. Extinction due to silicate grains in the far-infrared (FIR) will be measured in a Fourier Transform Spectrometer (FTS), with supporting data at millimeter wavelengths provided by measurements in a waveguide. We will also measure the emission from these materials in the mid- to far-infrared using three complimentary experimental setups; a radiometric system, a thermal emission system, and a calorimetric emittance test. The optical properties of silicates will be measured over a wide range of temperatures, and magnesium-rich silicates will be tested in aggregate and crystalline form. We will employ these data to determine complex dielectric constants for the materials and predict spectral signatures that are present in astronomical objects.



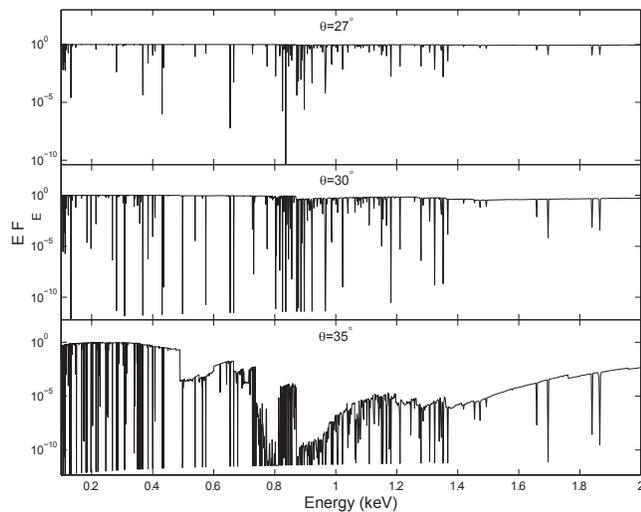
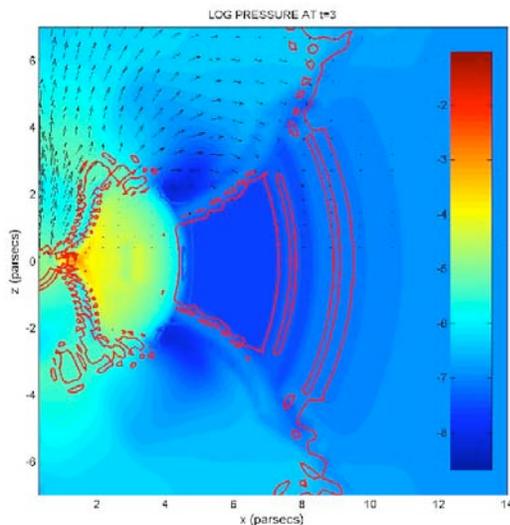
In astronomical environments, silicate dust typically forms from the gas phase (d) into a highly chaotic condensate (c). Through annealing, the condensate can turn into a more ordered melt (or glass) containing some individual crystalline structures (b). Such annealing can occur, for instance, in the hot environment surrounding young stars. On Earth, silicates are often found in pure crystalline form (a), usually in metamorphic rock. Much laboratory work done to date has focused on analysis of such minerals, despite the fact that the high pressures needed to produce these highly ordered states does not exist in astronomical environments. Credit: NASA/OPASI-T.

The data obtained through the OPASI-T program is critical for interpretation of astronomical spectra obtained at long wavelengths. With the impending launch of Herschel and the capabilities provided by SOFIA, this will help address a wide range of astronomical questions. Primary funding for OPASI-T is through the ROSES APRA program, with a period of performance through FY10. Additional funding has been provided through the ESA's Herschel program.

### Why do we see only outflow from objects which must be driven by inflow?

#### Atomic Data for X-ray Astrophysics

The grating instruments on the Chandra and XMM-Newton satellites have revealed the existence of absorption by partially ionized gas in many X-ray sources. These most notably include active galactic nuclei (AGN), as well as black holes and some neutron-star sources in our galaxy. The X-ray “warm absorber” spectra typically contain hundreds of identifiable absorption lines and are most often blueshifted by 100–1000 km/s, superimposed on the compact object's continuum radiation. The blueshift implies the existence of outflowing material, and simple estimates suggest that this can have important astrophysical im-



Gas pressure contours and velocity vectors (left) and synthetic spectra for a simulation of a warm absorber flow from torus evaporation. This is one scenario that may explain AGN warm absorbers. Credit: NASA/GSFC

#### On the Web

XSTAR home page

[heasarc.nasa.gov/lheasoft/xstar/xstar.html](http://heasarc.nasa.gov/lheasoft/xstar/xstar.html)

plications. Why do we see only outflow from objects which must be driven by inflow (accretion)? Does the outflow feed back its energy and gas to the host galaxy, thereby somehow coupling the accretion flow close to the black hole with the surroundings on a larger scale?

For the past six years, Kallman and colleagues have carried out a campaign to study warm absorbers and related X-ray spectra. These efforts can be divided into three components:

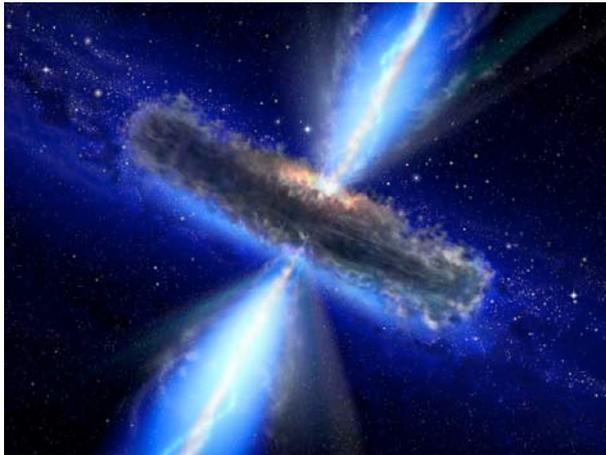
- Ab initio calculations of atomic data unavailable from other sources. This consists primarily of inner shell photoionization cross-sections and related quantities (fluorescence line widths and energies). It makes use of the R-Matrix suite of atomic codes developed by M. Seaton and collaborators in the UK.
- Hydrodynamic models for one possible scenario to explain AGN warm absorbers. This is an evaporative flow from the molecular torus responsible for obscuring the central black hole in type 2 AGN.

- Support for a publicly available modeling code and related projects which is in widespread use in the X-ray astronomy community for modeling these spectra.

### The Swift BAT AGN Survey

During the last four years, the Swift Burst Alert Telescope (BAT) has been surveying the sky in the hard (15–200 keV) X-ray band while awaiting gamma-ray bursts. Because of its very wide field of view, the BAT obtains more or less uniform sky coverage and very deep exposures (on average more than 4 million seconds) compared to the smaller fields of view and shorter exposures of Integral. Thus, the BAT has obtained the most uniform and deepest exposures of the hard X-ray sky.

The BAT sample is the first unbiased survey of active galactic nuclei (AGN) in the local universe. Because of the hard X-ray bandpass, there are no selection effects due to obscuration, galaxy properties or optical or radio properties because the hard X-rays pass through the obscuring material. We now know from Chandra and XMM observations and models of the X-ray background that most AGN are obscured in the optical and UV by dust and gas in the line of sight. The BAT



Swift's BAT Hard X-ray Survey offers the first unbiased census of active galactic nuclei in decades. Dense clouds of dust and gas, illustrated here, can obscure less energetic radiation from an active galaxy's central black hole. High-energy X-rays, however, easily pass through. Credit: ESA/NASA/AVO/Paolo Padovani

data allow a direct comparison of selection effects for AGN across the electromagnetic spectrum.

**BAT-selected AGN galaxies are found much more often in close pairs/mergers (30–50%) than field galaxies (1–3%), which supports theoretical ideas about how AGN activity is triggered in the local universe.**

Because of the relatively low (compared to Chandra) BAT sensitivity, the majority of the objects are close ( $\langle z \rangle \sim 0.03$ ) and bright ( $M_j \sim 11$ ) allowing detailed analysis of the host galaxies, through optical, UV, and IR spectra of the AGN and host galaxy. In addition to a catalog of objects, the BAT survey provides x-ray spectra and long term light curves for all the sources. This data set has already produced 13 refereed papers on AGN properties and several more are in progress.

At the January 2009 AAS meeting, several of the newest results from the BAT survey were presented by Richard Mushotzky (X-ray Astrophysics Lab). These include:

- The discovery that the BAT-selected AGN live in galaxies in the “green valley,” i.e., between the blue and red peaks. Thus, the AGN is either cutting off star formation or is stimulated by star formation. The colors and magnitudes of the host galaxies at low  $z$  are different from that of the Chandra-selected objects at  $z \sim 1$ . The  $z \sim 1$  hosts are preferentially luminous red ellipticals, while the  $z \sim 0$  hosts are slightly more luminous ( $\sim 0.5$  mag than  $L^*$  spirals indicating a strong evolution in the AGN hosts).
- BAT-selected AGN galaxies are found much more often in close pairs/mergers (30–50%) than field galaxies (1–3%), which supports theoretical ideas about how AGN activity is triggered in the local universe and contradicts recent results from the SDSS AGN surveys.
- Either the Eddington ratios of type II AGN are systematically less than type I AGN or their bo-

lometric corrections are different, indicating that there are fundamental difficulties with simple geometrical unification models.

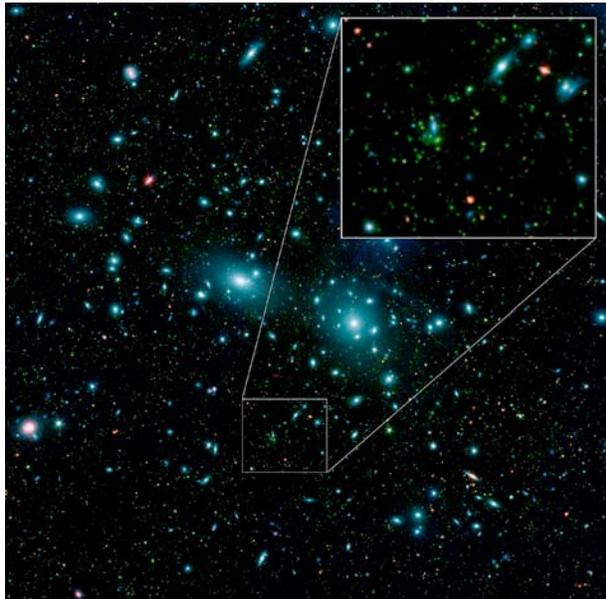
- There exist objects at low  $z$  that show no evidence of an AGN in the UV-IR bands, either through spectroscopy or imaging (e.g., HST NICMOS images). This shows that AGN surveys, even in the very nearby universe, are incomplete.

This work was part of the PhD thesis of Lisa Winter and of Mike Koss, both students at the University of Maryland, and Ranjan Vasudevan a student at Cambridge University.

### Studies of Galaxies, Including Groups and Clusters

Many people are working on galaxy evolution across several of the laboratories in the Astrophysics Science Division at NASA GSFC. A few recent projects being carried out by Bruce Woodgate et al. and Ann Hornschemeier, Jenkins, Hammer et al. are highlighted here.

The focus of Hornschemeier's work has been on the X-ray properties of galaxies, including the nature of



Spitzer IRAC data suggest the presence of a large population of dwarf galaxies in the Coma cluster that may be efficiently studied at infrared wavelengths. Credit: NASA/JPL-Caltech

the X-ray/star-formation-rate correlation. The X-ray/SFR correlation arises due to the regularity of the production of high-mass X-ray binaries in galaxies; there is also an analogous X-ray/stellar mass relation for low-mass X-ray binaries. Curiously, these correlations are found to hold across a broad range of galaxy properties. Recent work with Chandra and XMM has shown suppression in the X-ray emission (with respect to stellar mass and/or optical light) of galaxies in cluster and group environments versus the field (e.g., Hornschemeier et al. 2006). This may indicate a difference in the amount of X-ray emission per stellar mass, but current data are insufficient to tell. Hornschemeier (PI) is now conducting a large (0.5 deg<sup>2</sup> area) survey in an off-center region of the cluster with XMM-Newton (220 ksec). Preliminary analysis shows the suppression is indeed extreme and efforts are underway to obtain ground-based optical spectroscopic data (MMT Hectospec) and other multiwavelength data to make detailed measurements of the stellar population ages and star-formation histories of these galaxies.

**Galaxy X-ray emission appears to be suppressed with respect to stellar mass and/or optical light for galaxies in group environments. Efforts are underway to make detailed measurements of the star-formation histories of these galaxies.**

The Coma Hectospec data have demonstrated conclusively that cluster galaxies falling into Coma have younger ages and that significant quenching of star formation is occurring as galaxies fall into the cluster. The Spitzer IRAC data (PI, Hornschemeier) were published (with Jenkins) and show the possibility of a large population of dwarf galaxies that may be efficiently studied at infrared wavelengths. VLA work by Hornschemeier's team has demonstrated that there are few star-forming galaxies at faint radio luminosities, in contrast with local field RLFs. Their Coma GALEX survey provides measurement of the GALEX NUV and FUV luminosity functions (LFs), which are the deepest UV LFs measured for a cluster thus far (including dwarf early-type galaxies).



New high-resolution X-ray images from the Chandra X-ray Observatory, together with supporting observations from the Hubble Space Telescope (optical, shown here) and Spitzer Space Telescope (infrared), demonstrate that the nearby barred spiral galaxy NGC 1672 possesses a faint, central X-ray nucleus surrounded by an X-ray-bright circumnuclear ring of star-formation. Credit: NASA/STScI

Hornschemeier is also a coinvestigator on several Spitzer and HST projects to study twelve of the nearest Hickson Compact Groups to determine details of their star-formation histories. Data from these projects have shown that there is an “infrared color gap” between the early-stage compact groups (those just beginning to undergo interactions) and late-stage compact groups (dominated by ellipticals). It has also been shown that the IR spectral index can be used to identify active nuclei. There are also Chandra data on four of these galaxy groups, and Hornschemeier is collaborating with the Penn State Chandra ACIS team to study two more through Chandra guaranteed time.

Hornschemeier is working with John Mulchaey of Carnegie Observatories on a project to obtain wide-field optical imaging of all twelve of the HCGs as a precursor to a spectroscopic campaign to measure the LF. Currently, Panayiotis Tzanavaris has been leading the observing and data reduction for the spectroscopic campaign (for which we have obtained  $\sim 4$  nights of 12 thus far). Tzanavaris is also reducing Swift UVOT data that permits a detailed study of the star formation properties of these Hickson Compact Groups using higher resolution imaging ( $2''$ ) than is available with GALEX ( $5\text{--}7''$ ).

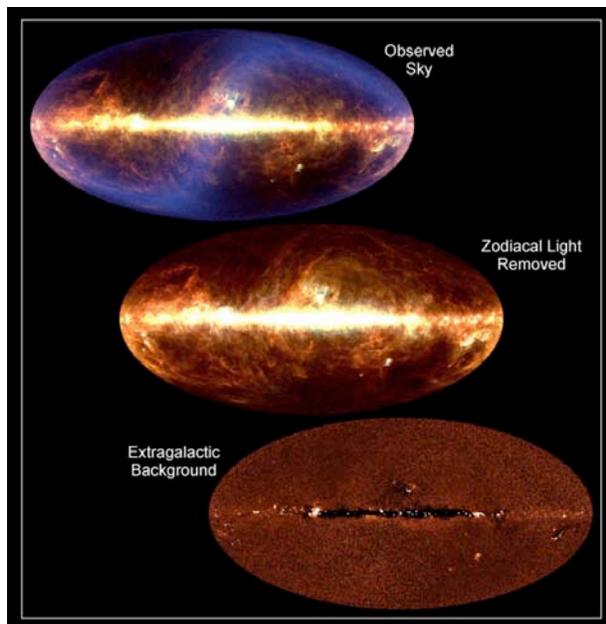
In addition to this group and cluster work, GSFC is heavily involved in study of individual galaxies and surveys of field galaxies. For instance, Leigh Jenkins et al. have been conducting a study to investigate how a strong bar affects the evolution of spiral galaxies, and in particular whether a bar can fuel active galactic nucleus (AGN) activity by funneling gas and dust in the galaxy disk toward the central region. Using new high-spatial-resolution X-ray imaging from the Chandra X-ray Observatory, together with supporting observations from the Hubble Space Telescope (optical) and Spitzer Space Telescope (infrared), Jenkins et al. have been able to demonstrate for the first time that the nearby barred spiral galaxy NGC 1672 possesses a faint, central X-ray nucleus surrounded by an X-ray-bright circumnuclear ring of star-formation. If the nuclear emission is due to low-level accretion onto an active supermassive black hole, this could be an example of a larger trend in which AGN activity is correlated with the presence of a strong bar, but obscured at optical wavelengths by star-formation activity in the same region. An initial investigation of more than 100 spiral galaxies observed with Chandra also shows some evidence that barred spiral galaxies may possess brighter X-ray nuclei, on average, than non-barred galaxies.

Large multi-color imaging surveys are becoming available with sufficient depth to enable investigations of the high-redshift universe. David Bonfield (former NPP Fellow), Bruce Woodgate, Carol Grady, Don Lindler, and collaborators are involved in this work. Lyman-alpha emission provides a unique locator of high-redshift active galaxies with sufficient redshift accuracy to identify cluster membership, to find knots in the cosmic web, and to study the interaction of active galaxies with the IGM. Woodgate et al. have begun a single-band excess search for high-equivalent-width emission-line galaxies using the SDSS2 supernova survey and the CFHT legacy survey for  $2.5 < z < 3$  galaxies with  $\sim 3,000$  times the search volume of all previous narrow band searches. In January they demonstrated its feasibility by finding a Lyman alpha emitting galaxy at  $z = 2.75$  by this method.

## Determination of the Cosmic Near-Infrared Background Through Studies of the Zodiacal Cloud

The Diffuse Infrared Background Experiment (DIRBE) instrument on the Cosmic Background Explorer (COBE) satellite was designed to measure the absolute brightness of the infrared sky in order to detect the extragalactic background light (EBL). At near-infrared (NIR) wavelengths, EBL contains the spectral signature of energy releases from primordial stars, the first objects to illuminate the universe after the cosmological dark ages. Furthermore, EBL is the repository of all energy released from subsequent generations of stars formed during the course of galactic cosmic evolution, as well as the gravitationally powered energy released by accreting black holes in active galactic nuclei (AGN). Knowledge of the EBL at these wavelengths is therefore of prime cosmological interest, but its detection is impeded by the presence of strong foreground emission components.

Detection of the Cosmic Infrared Background (CIB) first requires the removal of the zodiacal light, followed by



In order to reveal the EBL intensity in data from COBE's DIRBE instrument, light sources within the solar system and the Galaxy must be subtracted. The blue S-shaped band in the all-sky view at top is thermal emission from the solar system's zodiacal dust cloud. Credit: NASA/COBE

removal of Galactic light. Models used for the subtraction of the zodiacal light are estimated to be accurate to a few percent of the zodiacal light intensity, but still are the main source of the large (20–50%) uncertainty of the near-IR EBL. We have therefore undertaken two projects that will provide a direct absolute measurement of the zodiacal light.

**Knowledge of the EBL at near-infrared wavelengths is of prime cosmological interest.**

**Determining the Near-Infrared Extragalactic Background Light through Absolute Measurements of the Zodiacal Light (Eli Dwek, PI).** The first method determines the absolute intensity of the sunlight scattered by the zodiacal (interplanetary) dust cloud in the J (1.25  $\mu\text{m}$ ) band by measuring Fraunhofer lines in the spectrum of the zodiacal light with a large étendue, high-resolution, ground-based spectrometer. These observations, combined with knowledge of the solar spectrum, will provide a measurement of the absolute brightness of the scattered light from the zodiacal light in the DIRBE J band.

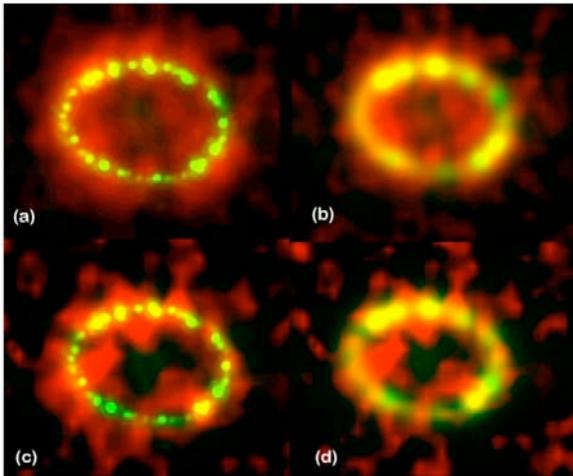
By carrying these measurements out in this spectral band of the Diffuse Infrared Background Experiment (DIRBE) aboard the COBE satellite, we will significantly improve the quality of the foreground subtraction of the DIRBE measurement and largely eliminate the major systematic uncertainty in the DIRBE determination of the NIR extragalactic background. Dwek's team (Arendt, Kutlyrev, Moseley, Silverberg) has designed and started to build a large étendue, high-resolution spectrometer to observe near-infrared solar absorption lines in the zodiacal light. They have recently acquired two silicon Fabry-Perot etalons, which are critical parts of the spectrometer, and verified their spectral performance using spectral line source in the lab. It is expected that the telescope will be assembled in Spring 2009; the first zodiacal light measurements will be obtained later that year.

**New Measurement of the Near-IR Extragalactic Background via Analysis of COBE/DIRBE Zodiacal Light Polarization (Richard G. Arendt, PI).** The second method will derive new measurements of the

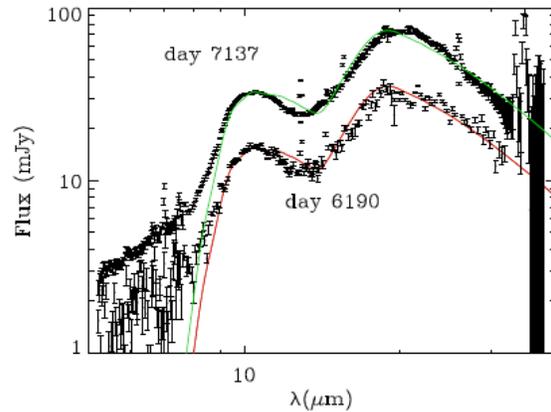
near-IR zodiacal light brightness through analysis of the previously unutilized polarization data obtained by DIRBE. The correlation of polarized and unpolarized intensities as a function of time provides a direct measure of the zodiacal light brightness relative to that of the Galactic and extragalactic backgrounds.

This analysis will provide a new model-independent means of removing the zodiacal light from DIRBE data. The integrated intensity of cataloged stars from the 2MASS survey will be used to subtract the bulk of the Galactic emission, with the remaining fraction subtracted using a model. The residual intensity will be that of the EBL. Previous estimates of the near-IR EBL intensity are unexpectedly larger than the integrated light of galaxies that can be individually resolved.

Our measurements will show whether the EBL really does contain a relatively bright and unresolved component or that the excess emission is only due to underestimated zodiacal light intensities. The EBL intensity



Top left: This view combines the mid-infrared 11.7  $\mu\text{m}$  image of the SN 1987A's equatorial ring (red) with the HST F625W image obtained on day 6502 (yellow). Top right: The same view as at left, but with the HST image convolved to match the resolution of the T-ReCS 11.7  $\mu\text{m}$  image. Bottom left: This view merges the Qa image from T-ReCS with the HST F625W image. Bottom right: The same view as at left, but with the HST image convolved to match the T-ReCS Qa angular resolution. Credit: NASA/Dwek et al.



The IR spectrum of the ring is dominated by emission from silicate dust, and evolving with time. Credit: NASA/Dwek et al.

is one of the most critical constraints in determining what future NASA missions like JWST will observe in deep imaging of the early universe.

### The Infrared and X-ray Evolution of SNR 1987A: Analysis of the Supernova Blast Wave Interaction with the Surrounding Medium

SN1987A is the most dramatically evolving supernova remnant (SNR) in the universe. Since its explosion on February 23, 1987, in the Large Magellanic Cloud, SN1987A has evolved from a supernova dominated by the emission from the radioactive decay of  $^{56}\text{Co}$ ,  $^{57}\text{Co}$ , and  $^{44}\text{Ti}$  in the ejecta to a supernova remnant whose emission is dominated by the interaction of the supernova blast wave with its immediate surrounding medium. This interaction is presently dominated by the inner equatorial ring (ER).

Observations of the remnant with the Hubble Space Telescope since 1994 have revealed spectacular images of “hot spots” strung along the ER like beads on a necklace, with new spots continuing to appear as the blast wave propagates into the ring. These hot spots appear to be finger-like protrusions, representing the first ER material to be hit by the blast wave. Images of the ER obtained at 0.3–8 keV with the Chandra X-ray Observatory, at 12 mm with the Australian Telescope Compact Array (ATCA) at the Australian Telescope Facility, and at 11.7 and 18.3  $\mu\text{m}$  with the T-ReCS mid-infrared imager at the Gemini-S 8m telescope

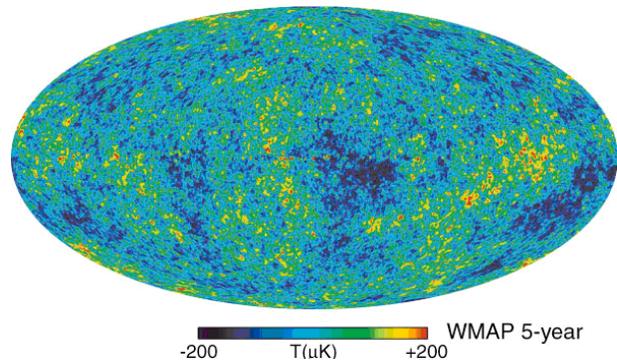
show an overall similar morphology, characterized by similar mean radii and surface brightness distribution.

The X-ray emission is thermal emission from the very hot plasma, shock-heated to temperatures in excess of  $3 \times 10^6$  K by advancing, reflected, and transmitted shocks generated by the supernova blast wave. The optical emission arises from denser gas that is shocked by transmitted shocks in the ER, and the radio emission is synchrotron radiation from shock-accelerated electrons. The mid-infrared emission observed by Spitzer is comprised of line and continuum emission. The lines most likely originate from the optically bright dense knots, whereas the continuum that dominates the spectrum is thermal emission from collisionally heated dust residing in the X-ray emitting plasma.

The morphological similarity between X-ray and mid-infrared images of the ring demonstrates the dust resides within the hot X-ray emitting plasma. Consequently, combined Spitzer infrared spectra and X-ray observations of the ER provide important complementary information on the evolution of the interaction of the supernova blast wave with its dusty surroundings.

**The ratio between the IR and X-ray flux emitted by the shocked plasma decreases with time. This provides the first observational evidence for grain destruction on a dynamical timescale.**

Eli Dwek and colleagues have carried out repeated infrared (IR) observations with the Spitzer satellite in order to follow the evolution of the infrared emission from SNR 1987A, in coordination with teams monitoring the remnant with HST, Chandra, and ground-based telescopes. The analysis by Dwek et al. has shown that the IR emission arises from silicate dust collisionally heated by the X-ray emitting plasma to temperatures of about 180 K. Comparison with the X-ray emission has shown that the ratio between the IR and X-ray flux emitted by the shocked plasma decreases with time, providing the first observational evidence for grain destruction on a dynamical timescale.



The full-sky map of the CMB temperature anisotropy from the five-year WMAP data. The foreground signals are greatly reduced using WMAP's multi-frequency data. Credit: NASA/WMAP

Observations of the ER show that the IR light curve is continuing to evolve, suggesting significant changes in blast wave-ER interaction. The rapid changes observed in the IR spectrum of the ER are also seen in its optical and X-ray morphologies and are manifestations of the multifaceted interaction of the supernova blast wave with the complex structure of the ring.

### WMAP Five-Year Results

WMAP helped establish a simple and comprehensive cosmological model that connects the physics of the very early universe to the properties of the universe today. In this standard model, the universe is flat, homogeneous and isotropic on large scales. The universe is composed of radiation and atoms, but it is currently dominated by dark matter and dark energy.

The first results from WMAP, based on one year of data, were released in 2003 and were followed up by three-year results in 2006. In 2008, the WMAP team released seven papers with results based on five years of data. The WMAP team at GSFC includes ASD scientists Hinshaw, Wollack, Kogut, and Bennett (now at JHU).

For Gaussian random-phase fluctuations, the angular power spectrum encodes the full statistical information in the map. Classic papers (Peebles and Yu, 1970; Sunyaev and Zeldovich, 1970) relate the properties of the universe to the structure in the angular power spectrum.

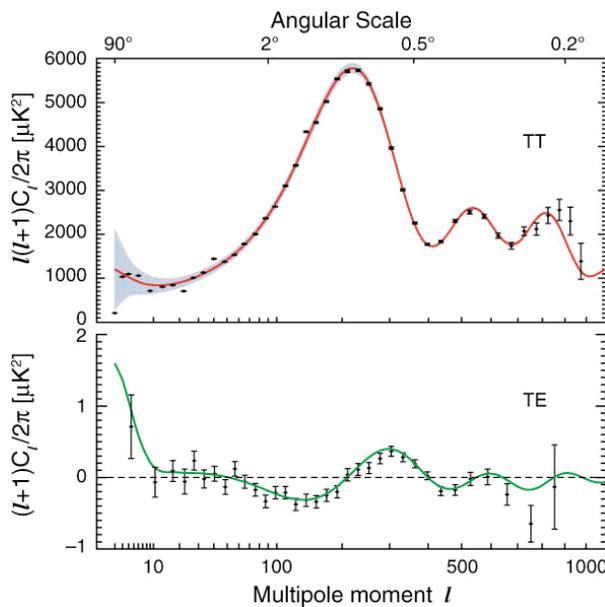
Best-fit  $\Lambda$ CDM parameters with five-year WMAP data

| $\Lambda$ CDM Parameter                 | WMAP data only       | WMAP+BAO+SNe          |
|---|----------------------|-----------------------|
| Matter density, $\Omega_m h^2$          | $0.123 \pm 0.006$    | $0.1369 \pm 0.0037$   |
| Baryon density, $\Omega_b h^2$          | $0.02277 \pm 0.0006$ | $0.02265 \pm 0.00059$ |
| Cosmological constant, $\Lambda$        | $0.742 \pm 0.030$    | $0.721 \pm 0.015$     |
| Scalar index, $n_s$                     | $0.963 \pm 0.014$    | $0.960 \pm 0.014$     |
| Optical depth, $\tau$                   | $0.087 \pm 0.017$    | $0.084 \pm 0.016$     |
| Amplitude at $8 h^{-1}$ Mpc, $\sigma_8$ | $0.796 \pm 0.036$    | $0.817 \pm 0.026$     |

The standard  $\Lambda$ CDM model, defined by the six parameters given in the table, is a good fit to the five-year WMAP data, with  $\chi_\nu^2 = 1.06$ . The model also fits the combination of WMAP data, baryon acoustic oscillations (BAO) data in the galaxy distribution, and supernovae (SNe) distance data.

With five years of data, WMAP has improved its measurements of sub-degree scale fluctuations, especially the third acoustic peak. By improving the precision

of the third peak, WMAP more accurately determines the cold dark matter density. This parameter is of great interest to both cosmologists and particle physicists. For cosmologists, it better constrains  $\sigma_8$ , the amplitude of matter fluctuations, and is an important input to dark energy constraints and cosmological simulations. For particle physicists, it constrains the dark matter self-annihilation cross-section.

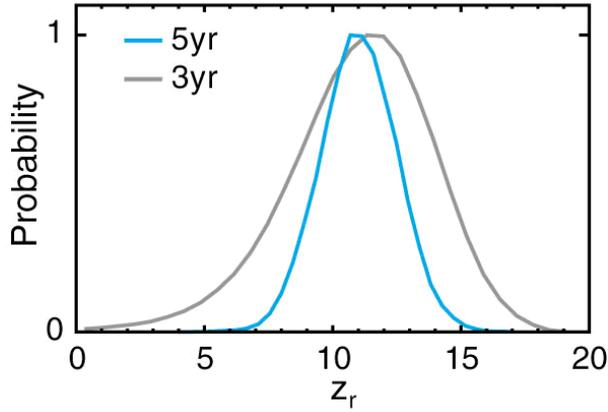


Top: The temperature (TT) spectrum of the 5-year WMAP data. The red curve is the best-fit  $\Lambda$ CDM model and the grey band is its cosmic variance uncertainty. With five years of data, the third acoustic peak is now coming into WMAP's view. Bottom: WMAP's temperature-polarization (TE) cross-power spectrum. This mostly arises from CMB scattering at  $z = 1090$ ; the rise at the lowest multipoles is due to reionization at  $z \sim 11$ . Credit: NASA/WMAP

**The WMAP five-year data have improved its measurements of sub-degree scale fluctuations, especially the third acoustic peak, and provide new evidence for the existence of a cosmic neutrino background.**

By combining WMAP data with other data sets that measure the kinematics of the local universe, we further improve some of the cosmological parameters (see table). The Hubble constant from WMAP data combined with SNe and galaxy BAO data yields  $H_0 = 70.1 \pm 1.3$  km/sec/Mpc. This  $< 2\%$  measurement of the Hubble constant is remarkable because it agrees closely with the results of more traditional means of measurement, which inspires strong confidence in the consistency of the cosmological model. It's worth noting that measurement of the Hubble constant to a factor of 2 dominated much of the last 75 years of astronomy. Likewise, the age of the universe as measured by WMAP— $13.73 \pm 0.12$  Gyr—is a  $< 1\%$  measurement.

The polarization data have improved significantly with five years of WMAP data. The polarization (EE) power spectrum is now detected at  $5\sigma$  in the multipole range of  $2 \leq l \leq 7$ . This has important implications for the



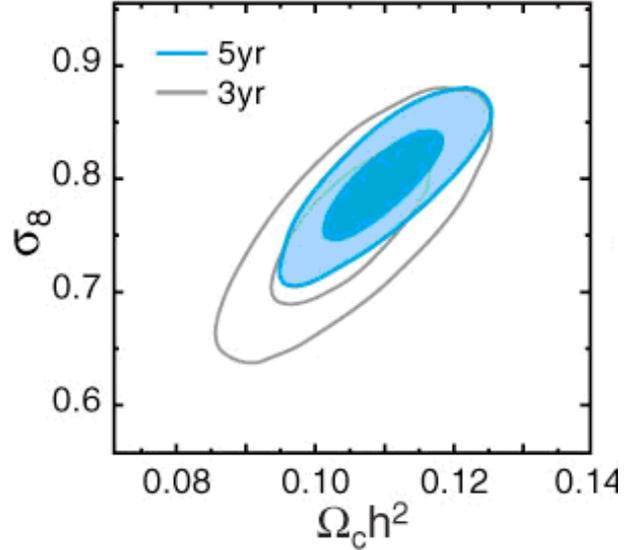
The likelihood for the redshift of sudden reionization. Although the maximum likelihood value is virtually unchanged from the three-year value, the data now significantly excludes sudden reionization at  $z \sim 6$ . Credit: NASA/WMAP

epoch of reionization, and WMAP data has improved the determination of its redshift.

With the three-year data, WMAP detected the signature of reionization in the EE power spectrum. Quasar absorption-line data show that reionization was occurring at  $z \sim 6$ . With the five-year data, WMAP has shown that the bulk of reionization was significantly earlier than  $z \sim 6$ , and that the absorption-line data probes the tail end of the process. The WMAP five-year data are now powerful enough to show that reionization was an extended process.

The WMAP five-year data provide new evidence for the existence of a cosmic neutrino background: relativistic neutrinos are required by WMAP data alone at  $> 99.5\%$  confidence, consistent with constraints from big bang nucleosynthesis, which probes an earlier epoch in cosmic history. Upper limits on the tensor-to-scalar ratio,  $r$ , a measure of the gravitational wave background produced during inflation, improved by 50% to  $r < 0.2$  (95% CL), and the upper limit on the bispectrum amplitude,  $f_{\text{NL}}$ , a measure of non-Gaussianity, has decreased by 30%.

For all of these cosmological results to be meaningful, the systematic measurement errors must be extremely well understood. Enormous effort has been expended to characterize the WMAP experiment: its calibration, systematic errors, noise properties, and foreground



The five-year WMAP data has brought about a significant improvement in the amplitude of the fluctuations,  $\sigma_8$ , and the cold dark matter density,  $\Omega_c h^2$ . Credit: NASA/WMAP

signals. These activities, which are intricate, challenging, and time-consuming, are the focus of the WMAP Team's effort.

## Results from ARCADE

The ARCADE project (Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission; Kogut, PI) released results from the 2006 flight. The principal result from this flight was the detection of an extragalactic radio background approximately six times brighter than the integrated emission from known populations of radio point sources. The ARCADE data are consistent with a superposition of a blackbody CMB plus a power-law radio background

$$T(\nu) = T_0 + T_{\text{BG}} \left( \frac{\nu}{\nu_0} \right)^\beta$$

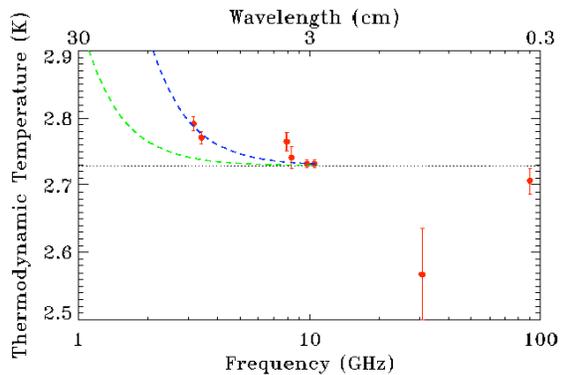
with parameters

$$T_0 = 2.729 \pm 0.004 \text{ K}$$

$$T_{\text{BG}} = 1.06 \pm 0.11 \text{ K}$$

$$\beta = -2.56 \pm 0.04$$

at reference frequency  $\nu_0 = 1 \text{ GHz}$ .



The sky temperature measured by ARCADE after subtraction of Galactic emission. NASA/ARCADE

The detected background cannot easily be explained as the integrated emission of faint radio sources. Extrapolating measured source counts to fainter fluxes would require an implausible source density  $\sim 8 \times 10^5$  per square arcmin at limiting flux 0.3 nJy.

Four papers describing the ARCADE instrument, the measurement of the sky temperature, the model of Galactic microwave emission, and the interpretation of the detected radio background have been submitted to *The Astrophysical Journal*. A press release described the ARCADE instrument and the radio background, and a press briefing was held at the January 2009 AAS meeting in Long Beach, Calif. ARCADE team members in ASD include Kogut, Wollack, Mirel, and Fixsen.

### Jets in Young Stars

Bipolar jets associated with pre-main sequence (PMS) stars are some of the most visually striking manifestations of star formation, providing a “fossil record” of the mass-loss history of the protostar. Such jets are most conspicuous when the star is obscured either by its natal molecular cloud material or, for older systems, when the star is viewed at high inclination (e.g., edge-on) to its circumstellar disk. The ease of detection of such jets led to the expectation that mass loss via jets was limited to the first  $10^5$  years of a protostar’s lifetime, was most common for low-mass protostars, and at 1–2 Myr was seen in only 30% of stars (Cabrit 2002). New jets continue to be discovered, even in well-studied star-forming regions, and associated with higher-mass stars (Devine et al., 2000; Grady et al.,

2004), indicating that jets are present over a wider range in stellar mass and age than previously suspected.

Biases toward higher mass-loss-rate jets in the broadband or forbidden-emission-line surveys (e.g., Kenyon et al., 1998) can obscure correlations that are diagnostic of structural changes in circumstellar disks. The low jet frequency noted by Cabrit (2002) appears to be a consequence of disk survival. For Taurus at 1–2 Myr, only 50% of stars have disks, with only 50% of PMS stars retaining disks at 1–2 Myr (Cieza et al., 2007), and that a further 10% of stars by that age have thermal emission deficits consistent with cleared lanes or central cavities in the disk. Some of these “transitional” disks are associated with binary stars (Ireland and Kraus, 2008), while others have the combination of large cavities and detectable on-going accretion that suggests dynamical clearing by Jovian-mass planets (Rice et al., 2006; Lubow and D’Angelo, 2006; Pontoppidan et al., 2008).

**ARCADE detected an extragalactic radio background approximately six times brighter than the integrated emission from known populations of radio point sources.**

Our pilot survey for jets in HST coronagraphically imaged PMS stars demonstrates that jets are found from stars with disks extending into the dust sublimation radius. Non-detections are preferentially found for the transitional disks. If supported for a larger sample of stars, these data would suggest that the disappearance of jet activity in PMS stars with disks may be one of the first remotely-detectable signatures of planet formation.

Bruce Woodgate and Carol Grady are carrying out such a larger survey with the Goddard Fabry-Perot (GFP) at the Apache Point Observatory 3.5m telescope. Their target list includes: approved Herschel targets (on the open-time key project, GASPS); planned H-band coronagraphic polarimetric differential imaging targets (as part of the Subaru Strategic Exploration of Exoplanets and Disks [SEEDS] study); and a few objects that have been proposed in the HST cycle 16 supplemental call. Previous spectral surveys for forbid-

den emission (Kenyon et al., 1998) and broadband direct-imaging surveys (Stapelfeldt et al., 2008) can detect suitably oriented jets down to mass-loss rates of  $10^{-8} M_{\odot} \text{ yr}^{-1}$ .

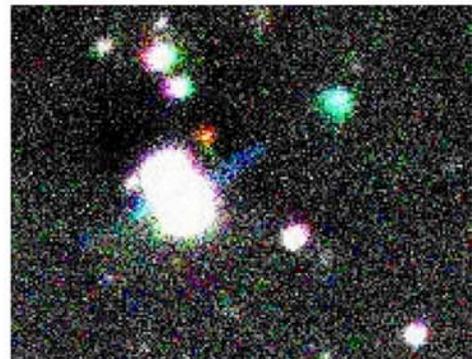
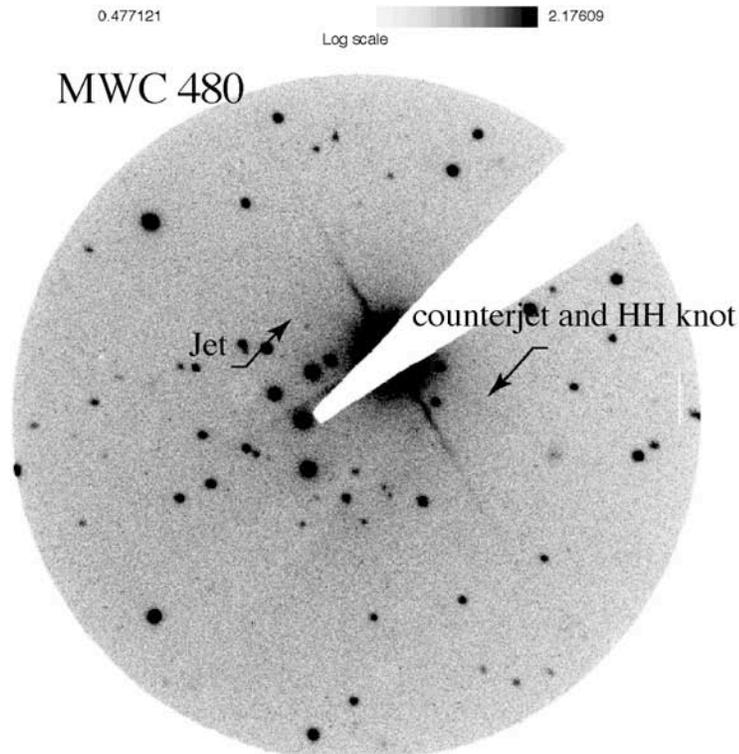
The GFP offers higher emission-line-to-star contrast (x 200–600, compared to HST broadband imaging) with its suite of medium-band filters and choice of Fabry-Perot etalons. In the event of bright nebulosity or a bright star, further contrast gains can be achieved using a coronagraphic wedge. The GFP has allowed detection of jets at lower mass-loss rates ( $5 \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ , MWC 480; Stecklum et al., 2009) well into the accretion-rate range of stars with transitional disks. In addition to jet detections, GFP data have proven invaluable in the interpretation of particular systems (e.g., PDS 144) and in planning high-contrast imaging. As of Nov. 2008, we have data for 50% of the SEEDS Taurus targets, the majority of the HST coronagraphically imaged Taurus T Tauri stars, and the

majority of the HST coronagraphically imaged Herbig Ae stars.

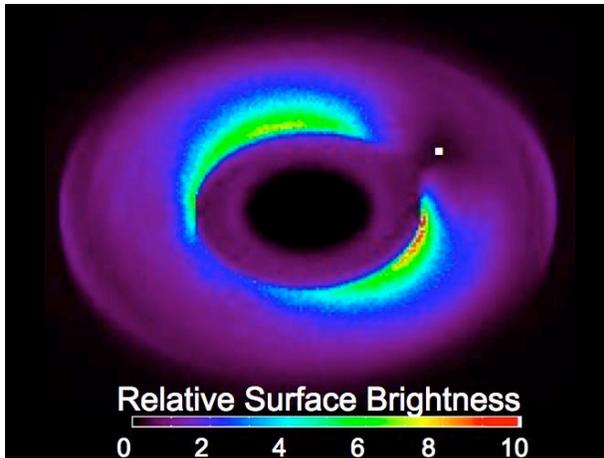
**Our pilot survey suggests that the disappearance of jet activity in PMS stars with disks may be one of the first remotely detectable signatures of planet formation.**

### Numerical Modeling of Planet-Disk Interactions

The recent discovery of a planet associated with the Fomalhaut debris disk has generated renewed interest in the physics of how planets shape circumstellar disks. Recognizing how planets can sculpt exozodia-



Left: Goddard Fabry-Perot  $H\alpha$  image of the Herbig Ae star MWC 480. The coronagraphic wedge is needed to enable jet detection against the bright light of the star. Right: GFP color composite detail of the PDS 144 system. The two bright stars in the field are  $5.4''$  apart. Jet emission is detected in  $H\alpha$ , with red indicating receding (counterjet) material, and blue approaching material. Decelerating HH knots are in green. The southern Herbig Ae star is slightly extended in our GFP imagery, which prompted reanalysis of archival HST imagery. We identified PDS 144 as an  $i \sim 70^\circ$  disk plus envelope, rather than a face-on disk. Credit: NASA



A ray-tracing non-plane-parallel radiative-transfer code predicts the appearances of disks shaped by hidden Jovian planets. This image shows the code applied to coronagraphic images of AB Aurigae. Credit NASA/GSFC

cal clouds, debris disks, and disks around young stellar objects can allow us to indirectly detect extrasolar planets that otherwise would go unseen and measure their masses and orbital parameters. This method may be the only way to detect extrasolar planets in long orbital periods (e.g.,  $\sim 100$  years) that are not self-luminous. Kuchner, his graduate student Christopher Stark, and postdoctoral fellow Hannah Jang-Condell work on this problem, modeling images of disks using NASA's supercomputers.

Except for the sun, the zodiacal cloud is the brightest component of the solar system in the optical and infrared. Proposed missions—like TPF, THEIA, NWO, ATLAST, ECLIPSE, EPIC, TOPS, etc.—that aim to directly image extrasolar analogs of the solar system must contend with light from zodiacal dust as potentially their primary astrophysical noise source. In particular, structure in exozodiacal clouds represents a challenge for these missions, since it can mimic the appearance of a planet.

Kuchner and Stark have developed a catalog of patterns that exo-Earths can create in exozodiacal clouds. This study (Stark and Kuchner, 2008) utilized a custom hybrid symplectic integrator to integrate the orbits of orders-of-magnitude more particles than previous simulations. It was the first to overcome the major source of noise that plagued prior simulations—uncertainty

in the populations of mean-motion resonances—and make quantitative predictions for the contrast of the dust rings associated with terrestrial exoplanets.

More massive debris disks like that around Fomalhaut have different physics than the solar zodiacal cloud; in these disks, the collision time is comparable to the Poynting-Robertson time for the dominant grain size. These disks will be key targets for JWST, ALMA, and many other future observatories. Kuchner and Stark have developed an algorithm for incorporating collisions into their disk modeling code. This algorithm self-consistently solves for the first time both the dynamical equations and the mass-flux equations for a debris disk containing a planet.

Hannah Jang-Condell has developed a ray-tracing non-plane-parallel radiative-transfer code for modeling images of T Tauri and Herbig Ae disks. By iteratively solving the equation of hydrostatic equilibrium and the radiative transfer, this code predicts the appearances of disks shaped by hidden Jovian planets. Jang-Condell and Kuchner are working on applying this model to recent coronagraphic images of the disk around AB Aurigae, which show structures consistent with the predictions of the models.

**Proposed missions that aim to directly image extrasolar analogs of the solar system must contend with light from zodiacal dust as potentially their primary astrophysical noise source.**

### Keck Interferometer Nuller Observations of Circumstellar Material

The Keck Interferometer Nuller (KIN) combines the mid-infrared light from the two Keck Telescopes to cancel out on-axis starlight and sense faint circumstellar material, like debris disks and exozodiacal clouds. Kuchner served as Science PI on the Keck Interferometer Nuller Shared Risk Science Team. Danchi and Barry also led aspects of this effort.

The first science result from the KIN and the Shared Risk Science Team was an observation of the nova RS Ophiuchi 3.8 days after its outburst (Barry et al., 2008). The data revealed the diameter of the dusty

nebula associated with this system and showed how the nebula near the white dwarf was chemically different from more distant parts. The observations support a model in which the dust appears to be present between outbursts—possibly in the form of a spiral shock wave caused by the motion of the star through the wind of the red giant—and is not created during the outburst event.

The second result from the KIN team is the measurement of resolved flux from the young debris disk 51 Ophiuchi (Stark et al., in prep.). Simultaneous modeling of data from the KIN, the MIDI interferometer, and Spitzer on this source point to a two-component disk: a radially confined edge-on ring of larger grains and an extended component of small grains, probably ejected from the inner “birth ring” of larger debris. In other words, 51 Ophiuchi appears to resemble other debris disks, like Vega, Beta Pictoris, and AU Microscopii, although the birth ring is much smaller—only  $\sim 10$  AU in size.

**The first science result from the Keck Interferometer Nuller was an observation of the nova RS Ophiuchi 3.8 days after its outburst that revealed the diameter of the dusty nebula associated with this system.**

As part of the Shared Risk effort, Kuchner and his students have developed a software package called ZODIPIC that simulates images of our zodiacal cloud around nearby stars for use interpreting KIN data sets. ZODIPIC incorporates a simple active-mesh al-



gorithm, an iterative dust-temperature calculator, and a library of optical constants that make it a general-purpose debris-disk modeling tool as well. ZODIPIC has become a popular tool for planning missions like TPF, NWO, JWST, etc.

#### *On the Web*

##### **Exozodi Simulation Catalog**

[asd.gsfc.nasa.gov/Christopher.Stark/catalog.php](http://asd.gsfc.nasa.gov/Christopher.Stark/catalog.php)

Kuchner now serves as PI on a Keck Interferometer Nuller key project that will follow up some of the sources observed during the Shared Risk time to make the deepest integrations ever made with the KIN. This data has just recently been acquired. Kuchner, Danchi, and Roberge all serve as coinvestigators on other KIN key projects

Kuchner is also the PI of a new study of circumstellar material using a different interferometer: a SIM Science Study aimed at measuring the sizes and shapes of Kuiper Belt Objects, centaurs and asteroids in our own solar system. SIM should be able to improve current size measurements for these objects by a factor of several, and directly sense their axis ratios and rotation axes. This study will examine limb-darkening corrections, tomographic shape reconstruction, and observing strategies, with the help of Jianyang Li, postdoctoral fellow at the University of Maryland.

#### **Resolved Observations of Debris Disks**

The Hubble Advanced Camera for Surveys (ACS) coronagraph has been the prime instrument for discovering new resolved debris disks. Clampin is a member of the ACS Science Team and led the team’s debris-disks theme. This sought to survey debris-disk candidates primarily selected from Spitzer IR excesses. He also collaborates with Paul Kalas’ team at Berkeley in following up ground-based coronagraphic observations of debris disks.

The primary motivation for attempting to obtain resolved imaging of debris disks is to understand how planetary systems evolve and to search for evidence of unseen planets in these debris-disk systems. Recent successes with the ACS disk program include new ob-

servations of HD 141569A (Clampin et al., 2003), which revealed detailed structures in the disk, and new disk discoveries such as HD 107146, the first G star with a resolved debris disk (Ardila et al., 2004), HD 92945 (Clampin et al., 2005), and HD 181327 (Schneider et al., 2006). Other solar type stars with debris disks discovered with ACS include HD 169344 and HD 51543 (Kalas et al., 2006).

**The exoplanet candidate Fomalhaut b lies in the plane of the Fomalhaut's dust belt. It lies approximately 119 AU from the star and 18 AU from the dust belt.**

One of the most intriguing results from ACS is the Fomalhaut system. In the course of observations designed to discover co-moving objects, a dust belt was discovered (Kalas et al., 2005). The dust belt was especially interesting as it exhibited two characteristics suggestive of the presence of an exoplanet: The belt is offset from the central star and its inner edge is sharp. This discovery prompted further observations of the Fomalhaut disk.

In the course of data analysis, a point source was found inside the belt in the approximate region where an exoplanet was predicted. The exoplanet candidate

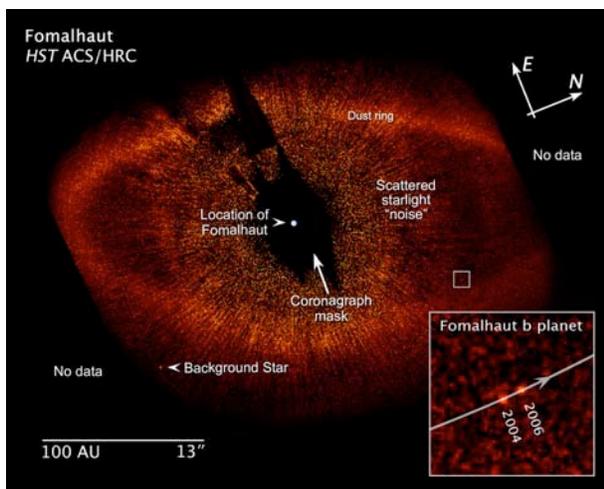
Fomalhaut b (Kalas et al., 2008) lies in the plane of the belt. It lies approximately 119 AU from the star and 18 AU from the dust belt. Observations separated by 1.73 years show evidence of counter-clockwise orbital motion. Dynamical models of the interaction between the planet and the belt indicate that the planet's mass is at most three times that of Jupiter for the belt to avoid gravitational disruption. The flux detected at 0.8  $\mu\text{m}$  is also consistent with that of a planet with mass no greater than a few times that of Jupiter.

The brightness at 0.6  $\mu\text{m}$  and the lack of detection at longer wavelengths suggest that the detected flux may include starlight reflected off of a circumplanetary disk with dimension comparable to the orbits of the Galilean satellites. We also observed variability of unknown origin at 0.6  $\mu\text{m}$ . Future observations of Fomalhaut are planned following the HST Servicing Mission in May 2009 to obtain an improved orbit for the exoplanet and a near-IR infrared spectrum.

#### *On the Web*

#### **The ZODIPIC IDL package**

[asd.gsfc.nasa.gov/Marc.Kuchner/home.html](http://asd.gsfc.nasa.gov/Marc.Kuchner/home.html)



Astronomers using the Hubble Space Telescope took the first visible-light snapshot of a planet orbiting another star. Fomalhaut b orbits inside the sharp inner edge of Fomalhaut's debris disk. Credit: NASA, ESA, and Z. Levay (STScI)



## IV. Research and Development

### *Suborbital Projects*

#### **Balloon-borne Experiment with a Superconducting Spectrometer (BESS)**

BESS is a highly successful U.S.-Japan program that uses elementary particle measurements to study the early universe. It provides fundamental data on the spectra of light cosmic-ray elements and isotopes. BESS is led jointly by GSFC (PI, John Mitchell) and KEK, the Japanese High Energy Accelerator Research Organization (PI, Akira Yamamoto). Hams and Sasaki are GSFC colleagues also working on the project. Collaborating institutions in the U.S. are the University of Denver and the University of Maryland, and in Japan the University of Tokyo, Kobe University, and ISAS/JAXA.

BESS measures the energy spectra of cosmic-ray antiprotons to investigate signatures of possible exotic sources, and it searches for heavier antinuclei that might reach Earth from antimatter domains formed during symmetry-breaking processes in the early universe. The BESS collaboration carried out nine conventional northern-latitude flights between 1993 and 2002, recording 2,237 cosmic-ray antiprotons and confirming that the majority are secondary products of the interactions of primary cosmic-ray nuclei with interstellar gas.

Flights near solar minimum in 1995 and 1997, however, observed low-energy antiproton flux slightly in



The BESS-Polar II instrument nears the start of its 2007 flight in Antarctica. Credit: NASA/BESS

excess of purely secondary expectations. This may suggest a contribution from an exotic primary source, such as the evaporation of small primordial black holes (PBH) with initial mass around  $5 \times 10^{14}$  g, or the annihilation of candidate dark matter particles.

**BESS-Polar I data provide the most stringent reported test of the presence of heavier antinuclei in the current universe.**

To continue this investigation with much greater sensitivity, the BESS-Polar instrument was developed for long-duration balloon flights over Antarctica. The BESS-Polar magnetic-rigidity spectrometer uses a unique superconducting magnet with thin coils and cryostat and a precision trajectory-tracking system. The charge and velocity of incident particles are measured by a plastic scintillator time-of-flight system with two layers at the top and bottom of the instrument and one layer below the tracker inside the magnet bore. A silica aerogel Cherenkov detector rejects light background particles. With geometric acceptances of  $\sim 0.3$  m<sup>2</sup> sr, BESS and BESS-Polar are the largest balloon-borne magnet instruments. In a single long-duration flight, the BESS-Polar exposure greatly exceeds that of the PAMELA satellite instrument.

GSFC is responsible for the outer scintillators, the instrument electronics, and the Cherenkov detector PMTs. BESS-Polar integration and testing take place at GSFC and GSFC co-leads launch and flight operations.

BESS-Polar I flew for 8.5 days in 2004—at a transient period prior to solar minimum—and reported 1,512 antiprotons. BESS-Polar II recorded data with the magnet energized for 24.5 days in 2007–2008, flying at solar minimum, when the sensitivity of the antiproton measurements to a low-energy primary component is greatest, and is expected to have detected  $\sim 10,000$  antiprotons. Depending on the antiproton energy, this is 10–20 times the combined BESS 1995/97 statistics. The instrument performed very well, and analysis of the 13.5 terabytes of data obtained on 4.7 billion cosmic-ray events is well underway.



BESS-Polar II nears liftoff in 2007. Credit: NASA/BESS

No antinuclei heavier than antiprotons have been detected in BESS flights through BESS-Polar I. These data have provided the most stringent reported test of the presence of heavier antinuclei in the current universe, with a 95% confidence upper limit of  $2.7 \times 10^{-7}$  for antihelium/helium. If no antihelium is detected in BESS-Polar II data, this will be lowered by about a factor of  $\sim 3$ .

BESS has also carried out the only search to date for antideuterons, which may be produced in local processes—including the evaporation of PBH and supersymmetric particle annihilation—and has reported an upper flux limit of  $3 \times 10^{-4} \text{ (m}^2 \text{ s sr GeV/nucleon)}^{-1}$ . For logistics reasons, the BESS-Polar II instrument could not be recovered in 2008 after its flight, or during the 2008/09 Austral Summer. Recovery is planned for the austral summer of 2009/10, when the instrument will be returned to GSFC for refurbishment.

### Super Trans-Iron Galactic Element Recorder (Super-TIGER)

Super-TIGER is a new, large-area balloon-borne instrument under development by Washington University in St. Louis (PI, W. Robert Binns), Caltech, GSFC, and JPL. John Mitchell leads the Super-TIGER effort at GSFC and with co-investigators Christian, De Nolfo, Hams, Link, Sasaki, and Barbier (now at NASA HQ).

Super-TIGER will measure the individual abundances of elements over the range  $30 \leq Z \leq 42$  with high statistical accuracy to test and clarify the emerging model of cosmic-ray origin in OB associations and models

for atomic processes by which nuclei are selected for acceleration. Exploratory measurements with lower statistics will extend to  $Z = 56$ . Super-TIGER will also measure, with excellent statistical precision, the energy spectra of the more abundant elements  $14 \leq Z \leq 28$  at energies  $0.8 \leq E \leq 10 \text{ GeV/nucleon}$ . These measurements will permit a sensitive test of the hypothesis that microquasars or other phenomena could superpose features on the otherwise smooth energy spectra.

**Super-TIGER's measurements will permit a sensitive test of the hypothesis that microquasars or other phenomena could superpose features on the otherwise smooth energy spectra.**

Super-TIGER builds on the smaller TIGER instrument that was flown from Antarctica in 2001 and 2003 for a total of 50 days. It produced the first measurements of individual element abundances for  $^{31}\text{Ga}$ ,  $^{32}\text{Ge}$ , and  $^{34}\text{Se}$ . Super-TIGER measures the charge and energy of incident nuclei using three layers of plastic scintillator, together with Cherenkov detectors employing both acrylic and silica aerogel radiators. Scintillating optical fiber hodoscopes give the trajectories of individual particles to enable corrections for pathlength through the detectors, detector response maps, and interactions in the atmosphere and in the instrument.

GSFC is responsible for both the acrylic and aerogel Cherenkov detectors, the scintillators, the mechanical structure of the instrument and payload, and the high-



Detector configuration of the Super-TIGER instrument. Credit: NASA/Super-TIGER

voltage system. In addition, instrument and payload integration will be carried out at GSFC.

Super-TIGER has a total area of 5.6 m<sup>2</sup> and is only 60 cm thick to maximize its geometric acceptance. The detector layout and minimal column density give an effective geometry factor of 2.5 m<sup>2</sup> sr at  $Z = 34$ —seven times larger than TIGER. Super-TIGER can accomplish its goals in two typical long-duration Antarctic flights, with the first planned for 2012.

Super-TIGER is a forerunner of the ENTICE (Energetic Trans-Iron Composition Experiment) instrument on the OASIS (Orbiting Astrophysical Spectrometer in Space) mission. OASIS is under study with NASA funding as an Astrophysics Strategic Mission Concept and will be presented for consideration by the Astro2010 Decadal Survey. In a three-year mission, ENTICE would provide the first statistically significant elemental-abundance measurements in the actinide range.

### Cosmic Ray Energetics and Mass (CREAM)

The balloon-borne CREAM instrument was developed for direct measurements of cosmic-ray spectra  $1 \leq Z \leq 26$  at total energies greater than 10<sup>11</sup> eV to test models of cosmic-ray acceleration and to measure the energy-dependent abundance ratios of secondary cosmic-ray species to their primary progenitors to test models of cosmic-ray transport and storage in the Galaxy. The CREAM collaboration includes the University of Maryland (PI Eun-Suk Seo), GSFC, Pennsylvania State University, Ohio State University, Ewha Woman's University (Korea) KyungPook National University (Korea), KAIST (Korea) LPSC Grenoble

(France) CESR Toulouse (France), and UNAM (Mexico). At GSFC, Mitchell is the Institutional PI and Link is a coinvestigator. Barbier led the CREAM effort at GSFC until his move to NASA Headquarters in 2007; he is now a collaborator.

In a series of long-duration balloon flights, CREAM will accumulate the large exposure needed to measure the energy spectra of the most common elements up to about 10<sup>15</sup> eV. At these energies, measurements have depended on the detection by ground-based instruments of the showers of particles produced by interactions of primary cosmic rays in the atmosphere. These indirect measurements can only infer the identity of the incident particle. Direct measurements by CREAM will provide invaluable information on cosmic-ray composition, as well as the calibration data required to interpret airshower results.

The combined CREAM and airshower data will test models of Fermi shock acceleration of cosmic rays in supernova remnants. Standard models for this mechanism predict that a rigidity-dependent acceleration limit should be reached, resulting in a progressive composition change with increasing energy from dominance by light elements to dominance by heavier elements. CREAM measures the charge of incident



The 2007 CREAM-III launch from Antarctica. Credit: NASA/CREAM

nuclei using a plastic scintillator timing detector and a silicon pixel detector. Depending on the energy and species of the incident particle, its energy is measured by a silica-aerogel Cherenkov camera (CREAM-III, -IV), a transition radiation detector (CREAM-I), or a tungsten-scintillating optical-fiber calorimeter (all versions). The geometric acceptance of the TRD is  $\sim 1.3 \text{ m}^2\text{sr}$  and the effective geometric acceptance (including interactions) for the calorimeter is about  $\sim 0.3 \text{ m}^2\text{sr}$  for protons and greater for higher Z nuclei.

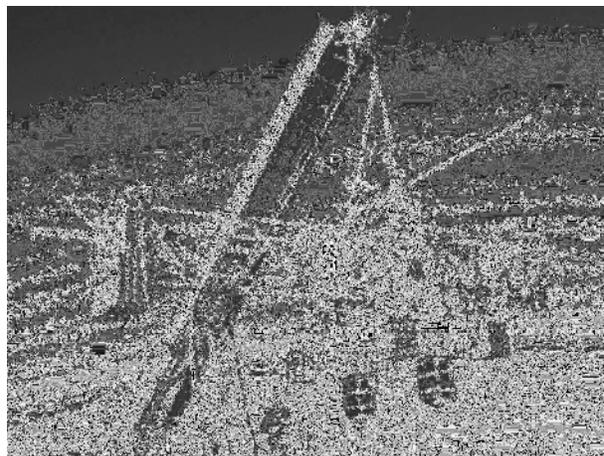
GSFC responsibilities are to provide an acrylic Cherenkov detector for rapid particle identification—to preferentially trigger the instrument on nuclei heavier than He—and a scintillating optical-fiber penetration detector that aids triggering on high-energy events and gives a reference time for the timing scintillators. GSFC also supports integration and test of CREAM as well as launch and flight operations.

**Direct measurements by CREAM will provide invaluable information on cosmic-ray composition, as well as the calibration data required to interpret airshower results.**

Originally designed for the anticipated ultra-long-duration balloon capability, CREAM has flown four times over Antarctica in conventional long-duration flights, accumulating 118.5 days of exposure: 2004–2005, 42 days; 2005–2006, 28 days; 2007–2008, 29 days; and 2008–2009, 19.5 days. The fifth flight of CREAM is planned for the austral summer of 2009–2010. For this flight, a new TRD is being prepared by CERN (Switzerland) and JINR (Russia) to facilitate improved measurements of secondary-to-primary ratios.

### **InFOCuS (International Focusing Optics Collaboration for $\mu\text{Crab}$ Sensitivity)**

InFOCuS is a balloon-borne hard X-ray instrument (Jack Tueller, PI). The instrument uses focusing optics to achieve high sensitivity in the 20–80 keV range, excellent spatial resolution ( $< 1 \text{ arcmin}$ ) and permits hard X-ray spectroscopy. Science goals include, for example, imaging sites of cosmic ray acceleration and



The InFOCuS flight gondola for the 2004 Campaign. Credit: NASA/GSFC

imaging  $^{44}\text{Ti}$  nuclear lines in young supernova remnants, imaging of radio lobes of AGN to determine intergalactic magnetic field, and direct imaging of faint AGN to study the hard X-ray background.

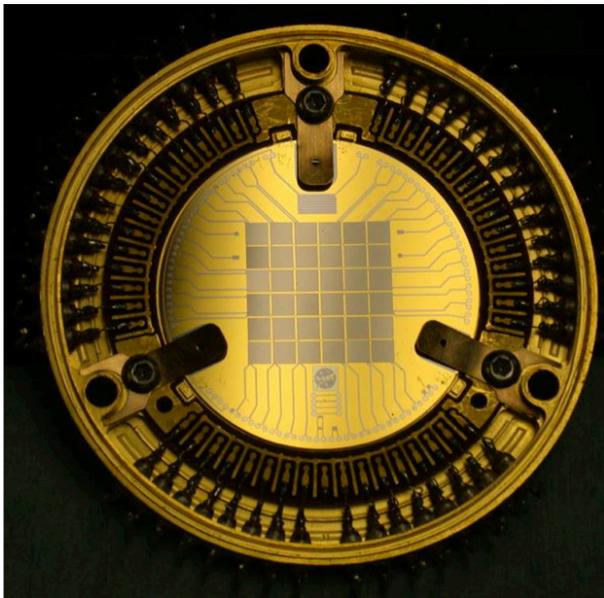
The design of sensitive hard X-ray instruments has traditionally been very challenging. However, developments in mirror and detector technologies, coupled with long-duration ballooning, have made possible sensitive observations in the hard X-ray band. CdZnTe is used for the detector material due to its excellent energy resolution. The mirror is a multi-layer-foil grazing-incidence mirror with focal length of 8 meters, but otherwise similar to the mirror produced at GSFC for Suzaku. The very long focal length required can be readily accommodated by a balloon instrument. The InFOCuS gondola has been built to provide accurate pointing accuracy and stability to take advantage of the spatial resolution afforded by the system. Besides providing interesting science, InFOCuS is also used as a technology pathfinder for future hard X-ray technologies.

InFOCuS has flown four times since 2000, and the next flight—from Alice Springs, Australia—is scheduled for 2010, with improved pointing control and detectors. The InFOCuS team is a collaboration of Goddard, Nagoya University, University of Arizona, and University of Maryland.

## X-ray Quantum Calorimeter (XQC) and Micro-X

The X-ray Quantum Calorimeter (XQC) is a broadband, non-dispersive X-ray spectrometer built to study the soft X-ray background in the band from 0.05 to 2 keV. The ASD research team members include Porter, Kelley, Kilbourne, Bandler, Adams, Eckart, Smith, Serlemitsos, and Soong. Collaborating institutions include the University of Wisconsin (Madison), MIT, University of Miami, University of Florida and the National Institute of Standards and Technology.

The spectrometer was built to differentiate the spectral components that are thought to make up the ubiquitous soft X-ray background, including emission from the Local Bubble, the Galactic halo, and solar-wind charge exchange in the exo-atmosphere and the heliosphere. The superposition of these temporally and spatially variable sources can create a complicated spectral picture that requires high-resolution spectroscopy to unwind. Detailed spatial maps first were made with sounding rockets, then with ROSAT, and the first high-resolution spectra in the 0.25 keV band



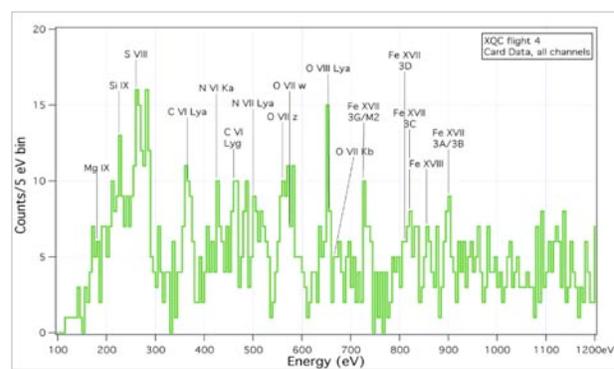
The XQC payload uses a 6x6 pixel X-ray calorimeter array developed and produced at GSFC. Each pixel in the array is 2 mm x 2 mm, and utilizes a 0.8- $\mu$ m-thick HgTe X-ray absorber. The detector array has an energy resolution better than 8 eV FWHM at 600 eV and has a nominal operating band from 0.05 to 2 keV. Credit: NASA/XQC

were made with the DXS shuttle-attached payload that used a scanning dispersive spectrometer.

**XQC payload is the first—and currently, the only—spaceflight implementation of an X-ray calorimeter array. Micro-X will provide some of the first detailed high-resolution spectra of a supernova remnant.**

The XQC, however, is the first broadband non-dispersive, high-resolution spectrometer to probe the entire X-ray-emitting range, from M-shell Fe emission at 70 eV up to 2 keV where the diffuse emission becomes dominated by unresolved extragalactic sources. In addition, the XQC payload is the first—and currently, the only—spaceflight implementation of an X-ray calorimeter array.

The XQC spectrometer is based on a 36 pixel X-ray calorimeter array that was designed and produced at GSFC. Each pixel in the calorimeter array is relatively large at 2mm x 2mm, and has an energy resolution at O VII Ka of better than 8 eV FWHM. The detector array is operated at 50 mK using a small adiabatic demagnetization refrigerator built at the University of Wisconsin. The payload does not use an X-ray optic since this would significantly reduce the grasp of the



Preliminary spectrum of the soft X-ray background centered at galactic coordinates  $30^\circ$ ,  $+60^\circ$  as observed with the XQC during its fourth flight in March 2008. The spectrum shows line emission from several highly charged ions and is likely a superposition of several emission mechanisms. Credit: NASA/XQC

experiment, but is instead collimated to a one-steradian field of view.

The XQC has flown four times since 1995, with the most recent flight in March 2008. The fourth flight used a detector array with four times the collecting area of previous flights and is based on technology developed for the Astro-E2 program. The data from the fourth flight is currently being processed, but preliminary results show significant contributions from C IV, O VII, OVIII, Fe XVII, and Fe XVIII. Previous flight have placed constraints on certain types of dark matter, and have detected and placed limits on Local Bubble emission from M-shell transitions in Fe IX, X, and XI. Flight five of the XQC is planned for late 2009 and will use a new, refined version of the large-area detector design for flight 4.

The Micro-X payload is designed to be the first X-ray calorimeter payload using focusing X-ray optics. It uses significant design heritage from the XQC program, including a very similar adiabatic demagnetization refrigerator. However, the detector and readout technology are derived from the Constellation-X (now IXO) program. The Micro-X payload will use a 121 pixel ( $11 \times 11$ ) X-ray calorimeter array with superconducting transition edge (TES thermistors) operating at 50 mK. It is designed to have an energy resolution of 2 eV (FWHM) across the energy band from 0.05 to 2 keV. The Micro-X payload will use a focusing optic designed and produced at GSFC for the SXS sounding rocket that flew in 1989 and is the predecessor of the optics used for BBXRT, ASCA, Astro-E2, and Astro-H.

The Micro-X payload is scheduled to fly during 2011 to observe the bright eastern knot of the Puppis-A supernova remnant. The detector array will be designed

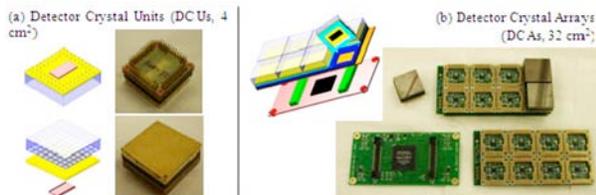
and produced by GSFC and will be read out using a cryogenic SQUID multiplexer and room-temperature electronics jointly developed by GSFC and NIST. GSFC will also provide the refurbished SXS X-ray optic with 200 cm<sup>2</sup> collecting area at 1 keV and a 2.5 arcmin PSF.

Micro-X will provide some of the first detailed high-resolution spectra of a supernova remnant, with about 40,000 counts expected during the flight. The payload will be the first opportunity to utilize high-spectral-resolution, broadband, spatial-spectral imaging, and will provide a glimpse of what we can expect from Astro-H and then IXO in the future.

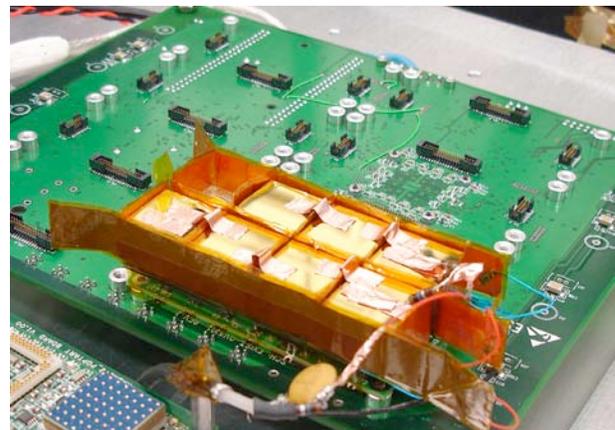
### Proto-EXIST

EXIST is a concept for an all-sky hard-X-ray imaging mission (see the mission concept section of this document for more information). ASD team members include Gehrels, Barthelmy, Tueller, Band, and Skinner.

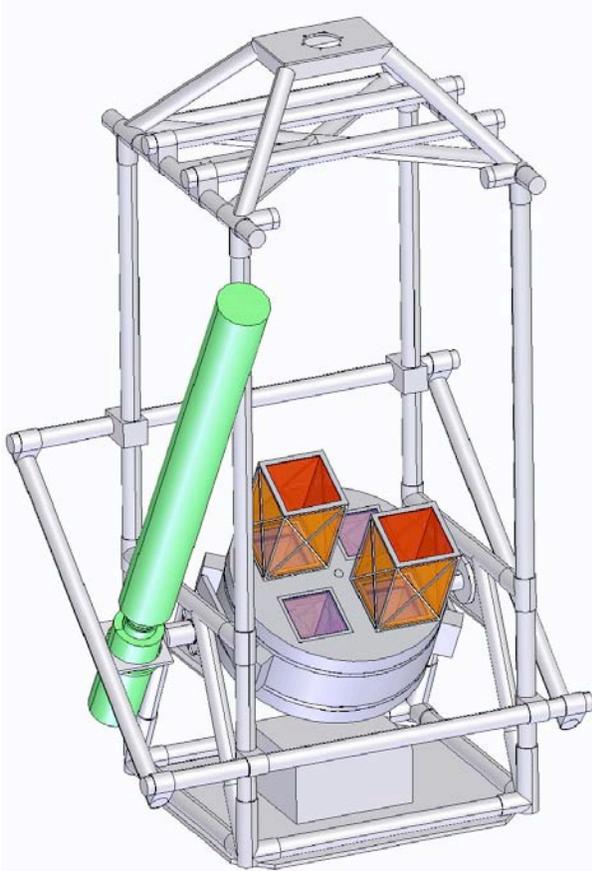
Proto-EXIST is a balloon-based instrument to develop the technology for the EXIST mission. It will fly in spring 2009 from Ft. Sumner, New Mexico. It is lead by Josh Grindlay (CfA), with significant contributions from Goddard. Goddard is developing the Command and Data Handling (C&DH) electronics in the front-end detector array electronics (i.e., everything after the detector ASIC).



Each of the eight Detector Crystal Units (DCUs, left) is a  $20 \times 20 \times 5$  mm CZT plus hybridizer board, plus ASIC. They plug into a Detector Crystal Array. Credit: NASA/GSFC



This photograph shows a single DCA plugged into an FPGA Controller Board (FCB), which holds eight of them. Four FCBs constitute the detector array for one of Proto-EXIST's two telescopes. Credit: NASA/GSFC

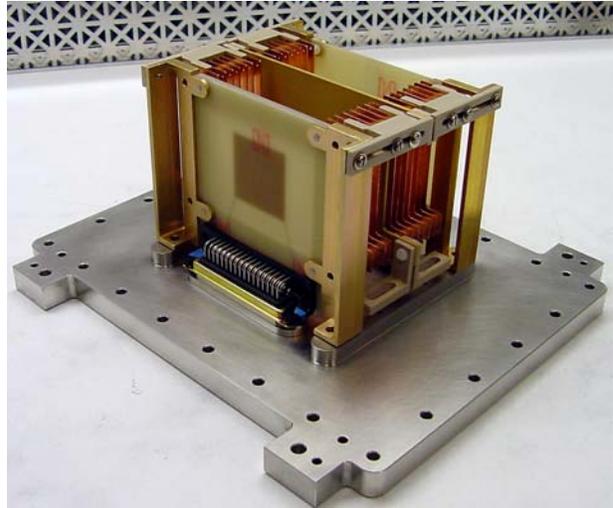


The Proto-EXIST balloon gondola, built by NASA's Marshall Space Flight Center, will hold two coded-aperture telescopes (orange) and a star camera (green) for absolute attitude information. The coded-aperture masks at the front end of the telescopes are not shown in this sketch. Credit: NASA/MSFC

### Gamma-Ray Burst Polarimeter

The Gamma-Ray Burst Polarimeter (GRBP) is an instrument designed for a small satellite called Mid-STAR-2 planned for launch by the U.S. Naval Academy (Joe Hill, PI, and K. Jahoda, co-I). The GRBP utilizes Time-Projection Chamber (TPC) technology in a new way to make polarization measurements of X-rays in the 2–10 keV energy band. The TPC polarimeter enables the design of much higher sensitivity and wider field-of-view instruments. GRBP is designed to satisfy three requirements:

- To demonstrate a new technology in a space environment for the first time.



This image shows the assembly of the first detector module for the Gamma-Ray Burst Polarimeter. Two detectors ( $3 \times 6 \text{ cm}^2$  area and 5 cm deep) share a single drift electrode (center) and the copper field-shaping electrodes on either side. Gold wire will complete the field shaping over the top of the detectors. Credit: NASA GSFC/USRA-CRESST/Southern Illinois Univ. at Carbondale

- To measure the polarization of the Crab Nebula, the only source for which the polarization has been conclusively measured in the X-ray band.
- To measure the polarization of 5 to 10 gamma-ray bursts (GRBs) in a two-year mission.

Polarization measurements of even a handful of GRBs will allow us to discriminate between different theories about the mechanisms behind these hugely powerful and enigmatic events. A demonstration of the GRBP instrument will increase the technology readiness level for future missions. This year, the GRBP team has designed and built one of the four GRBP modules. The module has been assembled and is currently undergoing test. Four of the six electronics boards have been prototyped and are being tested in the lab. The pre-amp board is in fabrication, with expected delivery at the end of January 2009. The design of the Command and Data Handling (C&DH) board is still in progress due to several changes in flight opportunity.

The design of the flight detector enclosure and detectors is almost complete but will not be completely finalized until we successfully complete the end-to-end

test at the beginning of March 2009. The flight designs of three of the six electronics board are complete and are in layout with delivery is expected at the end of April 2009.

**Polarization measurements of even a handful of GRBs will allow us to discriminate between different theories about the mechanisms behind these hugely powerful and enigmatic events.**

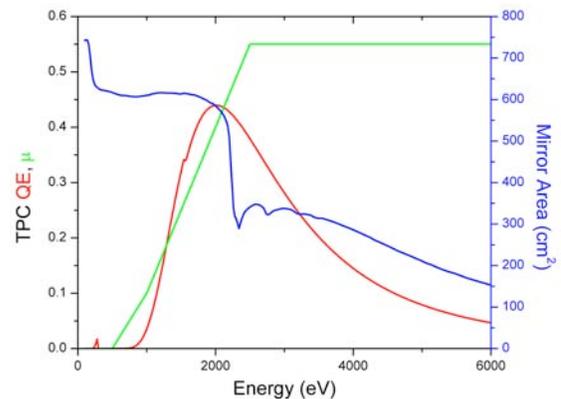
The MidSTAR-2 spacecraft has not yet been manifested, so the team has been investigating alternative launch opportunities. The most likely scenario that is compatible with the instrument delivery schedule is that GRBP will be tested on a sounding rocket. This will accomplish the first two goals and prove the design such that a satellite version could be built to measure the polarization of GRBs.

### X-ray Advanced Concepts Testbed (XACT)

XACT is a new suborbital X-ray payload being developed at GSFC to test and advance Technology Readiness Levels (TRL) of several technologies that could enable future missions (Gendrau, PI). The scientific objective of XACT is to measure the X-ray polarization properties of the Crab Nebula, the Crab pulsar, and of the accreting binary Her X-1. Polarimetry is a powerful tool for astrophysical investigation that has yet to be exploited in the X-ray band, where it could provide unique insights into neutron stars, black holes, and other extreme-physics environments.

With powerful new enabling technologies, XACT will demonstrate X-ray polarimetry as a practical and flight-ready astronomical technique. The technologies XACT will bring to flight readiness will also provide important new capabilities for NASA missions in space-based X-ray spectroscopy, timing and photometry. XACT combines new ultra-lightweight optics, advanced photoelectric X-ray polarimeters, and novel calibration sources in a standard sounding rocket payload.

The XACT optics—lightweight concentrators optimized for unresolved sources—will provide the larg-



This graph shows parameters relevant to XACT sensitivity as a function of energy: effective area of XACT optics, a pair of 25-cm diameter X-ray concentrators (blue), quantum efficiency (red) and modulation (green) of the TPC. Credit: NASA/GSFC

est focused X-ray-collecting area ever achieved on a sounding rocket. Currently under development at GSFC, they will have the largest focused collecting-area-to-mass ratio ever flown, enabling future space-based missions that require truly enormous throughput and low background.

**XACT will demonstrate X-ray polarimetry as a practical and flight-ready astronomical technique.**

The XACT polarimeters are the latest innovation in photoelectron tracking devices that combine a large polarization response with high quantum efficiency to achieve unprecedented sensitivity. ASD scientists recently originated this polarimetry technique, based on the negative-ion Time Projection Chamber (TPC), and are currently developing it for astrophysical and heliospheric missions in the 1–100 keV band. The TPC polarimeter was the basis for two recent Small Explorer proposals and is under development with GSFC internal R&D funds and in four ongoing ROSES-funded projects. XACT will leverage these efforts to deliver the polarimeters at a low incremental cost.

XACT will demonstrate in-flight calibration using a modulated electronic X-ray source that can be pulsed for arbitrary and commandable intervals. Such a source can be used to provide calibration information on demand. This minimizes the associated background and results both in higher sensitivity and observatory-scheduling freedom for future missions.

The XACT goals are accomplished with a simple flight plan that is well within the launch and recovery envelopes of a standard Black Brant IX at the White Sands Missile Range. The first launch will be in December 2011 to observe the Crab. This will be followed by a second launch in June 2012 to look at Her X1.

**Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission (ARCADE)**

The Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission (ARCADE; Kogut PI) is a balloon-borne instrument to measure the absolute spectrum of the cosmic microwave background and

diffuse radio continuum at the poorly measured centimeter wavelength band between the COBE/FIRAS measurements at millimeter wavelengths and radio surveys at long wavelength. ARCADE features a double-nulled instrument in a novel open-aperture cryogenic payload, with no windows between the cold (2.7 K) optics and the ambient atmosphere.

**ARCADE measured the blackbody spectrum of the cosmic microwave background with precision approaching that of the COBE/FIRAS instrument, despite the balloon environment.**

ARCADE measured the blackbody spectrum of the cosmic microwave background, finding a temperature  $T_0 = 2.729 \pm 0.004$  K with precision approaching that of the COBE/FIRAS instrument, despite the balloon environment. A major find was the detection of an extragalactic radio background some six times brighter



ARCADE takes flight July 2006. Credit: NASA/ARCADE



The ARCADE payload is prepared for launch at Columbia Scientific Balloon Facility in Palestine, Texas. Credit: NASA/ARCADE

than can be accounted for from the integrated emission of known populations of faint radio sources.

ARCADE also produced a number of technological innovations, including the development of a black absorbing paint, a calibration target with reflection less than -40 dB within a height  $0.7\lambda$ , and the demonstration of fully cryogenic open-aperture optics for a new generation of far-IR instrumentation.

### Primordial Inflation Polarization Explorer

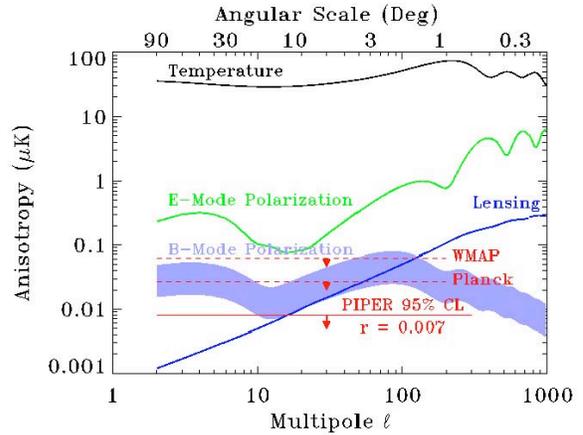
The Primordial Inflation Polarization Explorer (PIPER) is a new mission to measure the polarization of the cosmic microwave background to search for the signature of primordial gravity waves excited by an inflationary epoch in the early universe. Alan Kogut is the PI, and ASD team members include Benford, Chuss, Fixsen, Hinderks, Hinshaw, Moseley, Staguhn, and Wollack.

**PIPER will detect the signature of inflationary gravity waves to a factor of three fainter than the lowest value predicted by inflationary models.**

PIPER achieves unprecedented sensitivity by combining several technologies pioneered by Goddard researchers.

- Large-format bolometric detectors. PIPER will fly 5,120 transition-edge superconducting bolometers in a Backshort-Under-Grid (BUG) architecture.
- A Variable-Delay Polarization Modulator (VPM) injects a time-dependent phase delay between orthogonal linear polarizations to cleanly separate polarized from unpolarized radiation.
- Open-aperture cold optics. PIPER's twin telescopes fit within the old ARCADE dewar and will operate at 1.5 K to provide background-limited sensitivity.

PIPER will map the northern sky in both linear and circular polarization, at wavelengths 1500, 1100, 850, and 500  $\mu\text{m}$  (frequencies 200, 270, 350, and 600

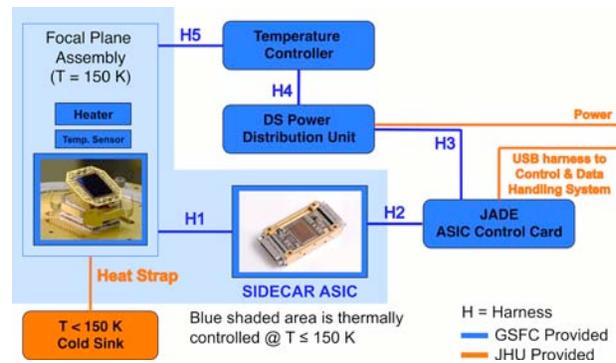


PIPER sensitivity (red) compared to the gravitational wave signal predicted by WMAP (blue band). PIPER is an order of magnitude more sensitive than the European Space Agency's planned Planck mission. Credit: NASA/PIPER

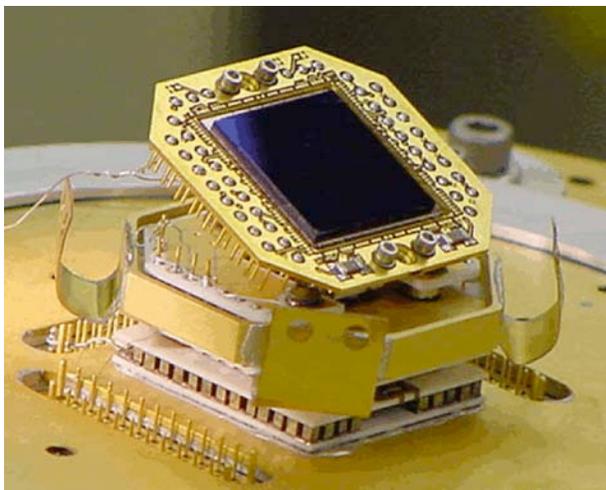
GHz). It will detect the signature of inflationary gravity waves to a factor of three fainter than the lowest value predicted by inflationary models. The unbiased survey of sub-millimeter polarization will also provide an important probe of the interstellar dust cirrus and the large-scale structure of the Galactic magnetic field.

### Absolute Color Calibration Experiment for Standard Stars (ACCESS)

ASD scientists Rauscher and Woodgate are collaborating with Johns Hopkins University in a series of rocket-borne suborbital missions to provide observations of standard stars for the Joint Dark Energy Mission



Researchers at GSFC and Johns Hopkins are collaborating on development of the ACCESS detector system. Credit: NASA/ACCESS



This HAWAII-1R SCA from Teledyne Imaging Sensors is used in Hubble's Wide Field Camera 3. It's similar to the one that will be flown by ACCESS. Credit: NASA.

(JDEM). The Absolute Color Calibration Experiment for Standard Stars (ACCESS; Kaiser, PI) will transfer the National Institute of Standards and Technology (NIST) absolute calibration standards to the bright stars Vega and Sirius with an accuracy and precision of  $< 1\%$ .

Establishing spectrophotometric standard stars to this precision is a critical requirement of type Ia-supernovae-based dark energy investigations, and it improves both the absolute and relative calibration that is the underpinning of the standard-star network and the basis of astrophysical calibrations. ACCESS also extends our understanding of stellar physics through observations of A-stars and cool stars.

GSFC is providing the ACCESS detector system (DS). The ACCESS DS leverages NASA's substantial investment in JWST and HST detectors. The focal plane array will be a  $1K \times 1K$  HgCdTe device, with the composition tailored to produce a long-wavelength cutoff at  $\sim 1.7 \mu\text{m}$ , and the CdZnTe growth substrate removed to provide high near-IR quantum efficiency and response through the visible to the near UV. Such devices have been pioneered for the HST/Wide Field Camera 3 (WFC3) program by Teledyne Imaging Sensors (TIS). The band gap corresponding to the  $1.7 \mu\text{m}$  cutoff yields low dark current at operating temperatures near 150K.

Ongoing work focuses on requirements development. In particular, the team is writing the functional and performance specification for the SIDECAR application specific integrated circuit (ASIC). Although the SIDECAR itself will be selected from non-flight JWST inventory and the thermal/mechanical interfaces are therefore defined, ACCESS requires some modifications to existing software. Because the ACCESS detectors will be selected from existing WFC3 inventory, modifying the SIDECAR software drives the critical path.

**Establishing standard stars to this precision is a critical requirement of type Ia-supernovae-based dark energy investigations.**

### *Technology Development*

#### **X-ray Calorimeter Development**

An X-ray calorimeter determines the energy of an incident X-ray photon by measuring a small change in temperature. Three types of X-ray calorimeters presently dominate the field, each characterized by the thermometer technology. The first two types use temperature-sensitive resistors: semiconductors in the metal-insulator transition and superconductors operated in the superconducting-normal transition. The third type uses a magnetic thermometer. These can be considered the three generations of X-ray calorimeters, although further development of each is proceeding.

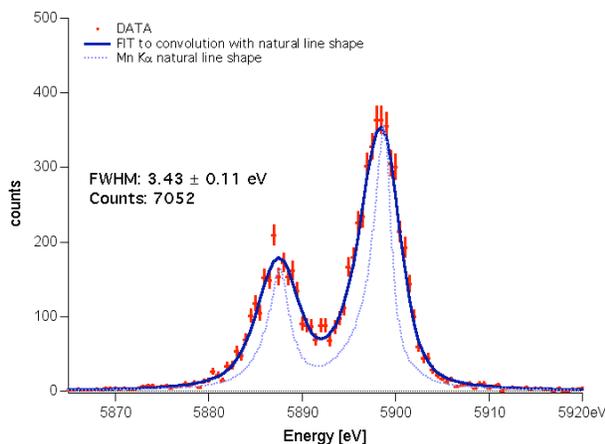
The Soft X-ray Spectrometer (SXS) on Astro-H, expected to launch in 2013, will use an array of silicon thermistors with HgTe X-ray absorbers that will operate at 50 mK. Both the semiconductor and superconductor calorimeters have been implemented in small arrays. Kilopixel arrays of the superconducting calorimeters are just now being produced, and it is anticipated that much larger arrays will require the non-dissipative advantage of magnetic thermometers. Goddard Space Flight Center is the only institution playing a leading role in the development of each of the three dominant X-ray calorimeter technologies. The ASD microcalorimeter team includes Simon Bandler, Rich Kelly, Caroline Kilbourne, Scott Porter,

postdocs Megan Eckart and Steve Smith, and coop student Jack Sadleir.

The main development in the silicon-thermistor calorimeters since XRS/Suzaku has been in their HgTe absorbers. GSFC has been working closely with EPIR, a company that was awarded an SBIR contract to develop HgCdTe material with substantially lower heat capacity than the material used for XRS that yet thermalizes the energy of X-ray photons reproducibly and uniformly. Although process refinement is still in progress, the GSFC calorimeter team plans to use this material in the SXS array. Better than 4 eV resolution at 6 keV has been achieved using samples of EPIR HgCdTe in the size needed for SXS (0.83 mm wide). The SXS thermistor array itself is based heavily on the XRS design, but will include better heatsinking to reduce the impact of cosmic-ray heating.

**Goddard Space Flight Center is the only institution playing a leading role in the development of each of the three dominant X-ray calorimeter technologies.**

Over the past few years, Goddard has developed a microcalorimeter design that incorporates a microns-thick Au or Au/Bi absorber, designed to thermalize the absorbed energy quickly, with a superconduct-



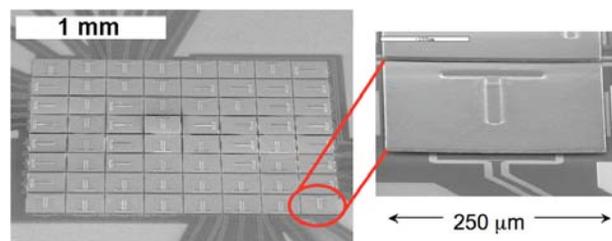
Mn K $\alpha$  spectrum measured with a silicon-based calorimeter using improved HgCdTe X-ray absorber material. Resolution better than 4 eV has been achieved in many pixels compatible with the design of the SXS of Astro-H.

ing transition-edge sensor (TES) made from a Mo/Au proximity-effect bilayer. In this novel design, the absorber makes direct contact with the TES only in normal-metal regions that are used to reduce noise in these sensors, which allows the use of a high-quality electroplated gold layer as the foundation for the absorber. A further constraint, that the high-conductance absorber not electrically short out the sensor, results in an unusual T-shaped geometry for the contact.

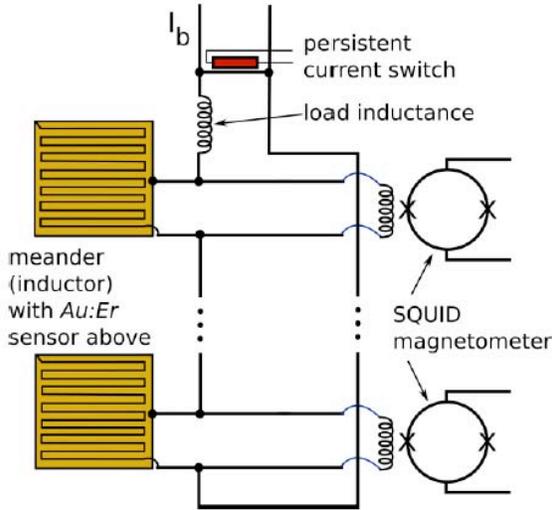
These devices consistently achieve energy resolutions of 2–3 eV FWHM at 6 keV. The pixels are sufficiently uniform that a 2x8 SQUID multiplexer read-out demonstration, done in collaboration with colleagues at the National Institute of Standards and Technology, achieved better than 3 eV resolution in all 16 pixels using the common biasing inherent to the design of the electronics. Fabrication of the first  $32 \times 32$  arrays has just been completed, and such arrays with the high-density microstrip wiring needed to read each pixel in the array will be produced in spring 2009.

Goddard has also developed position-sensitive TES calorimeters. These devices join multiple absorbers to a single TES via different thermal links, and the pulse shape is used to determine which absorber received the X-ray photon. Four-absorber versions have demonstrated an energy resolution of 6 eV at 6 keV, and variations with larger absorbers and with more absorbers are being studied.

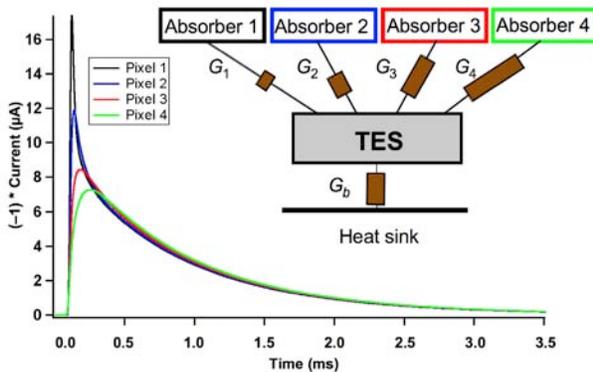
Goddard is part of an international collaboration (including Brown University, Heidelberg University, NIST/Boulder and PTB/Berlin) to develop magnetic calorimeters. The Goddard emphasis has been on designs that can be implemented in closely packed



This is electron micrograph of a uniform TES array with Au/Bi absorbers. The close-up view on the right shows an individual pixel. The absorber is cantilevered over the underlying substrate everywhere except in the T-shaped contact area.

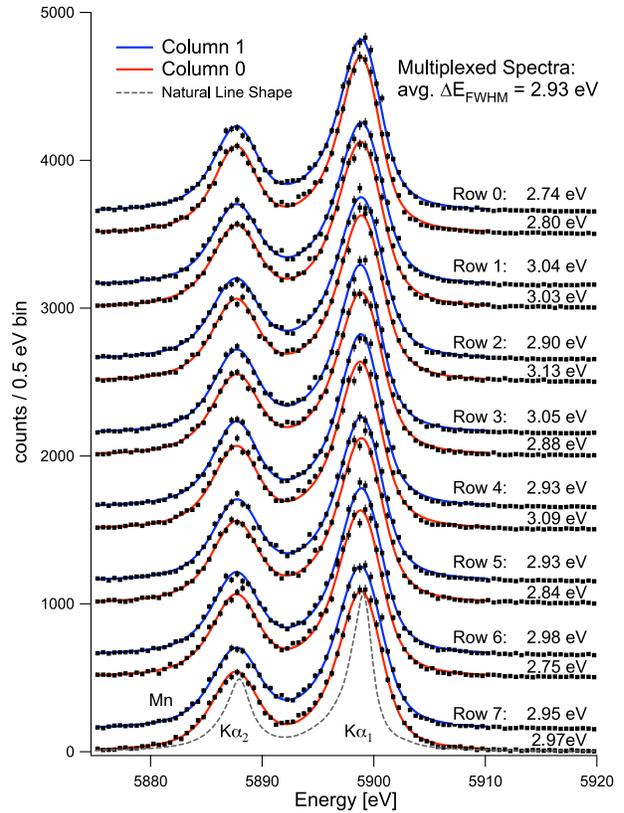


This view shows the read-out circuit for meander-based magnetic calorimeters. An X-ray absorber can be affixed to each meander, making possible very large, close-packed arrays.



Schematic of a position-sensitive calorimeter, in which four pixels are formed from four absorbers and a single TES. The graph shows 6 keV pulses measured experimentally by such a device. The absorbers are each connected to the TES with a different thermal link (G), so X-ray events in the four absorbers produce different pulse shapes.

arrays. Goddard has been fabricating arrays of superconducting niobium meander inductors onto which a layer of magnetic material (Au:Er) is deposited. When a current is passed through the meander, a magnetic field is produced in the magnetic material. When an X-ray is absorbed, the heating changes the magnetic permeability, and therefore the inductance of the meander. The change in inductance of the meander



Results of a two-column by eight-row multiplexing demonstration using a Goddard array and NIST SQUID multiplexing electronics at NIST. The black points show histograms of Mn K $\alpha$  X-rays from an <sup>55</sup>Fe source for each pixel acquired simultaneously, with vertical offsets for clarity and fits overlaid in blue/red.

changes the current both through the meander and through the input coil of the SQUID. The first magnetic calorimeter arrays with absorbers have achieved 5.4 eV resolution at 6 keV, and there remains potential to substantially improve on this in the near future, perhaps even to under 1 eV. Position-sensitive magnetic calorimeters analogous to the TES-based version are also under development.

### X-ray Mirror Development: IXO and NuSTAR

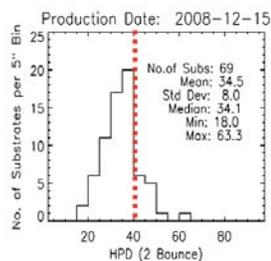
Mirror technology development for the International X-ray Observatory (IXO), formerly known as Constellation-X, continues at GSFC and is led by Will Zhang. Zhang and his team have all but demonstrated that the thermal glass slumping technology will not only meet the original 15" requirement, but also most likely will be able to achieve the 5" goal.

In November 2007, a pair of mirror segments were aligned and bonded for the first time and tested in an X-ray beam at ASD's X-ray beamline in Area 200 at GSFC, when an image quality of 14.7" was achieved. This result agrees well with theoretical predictions based on optical metrology of the mirror surfaces and validates the approach adopted for IXO.

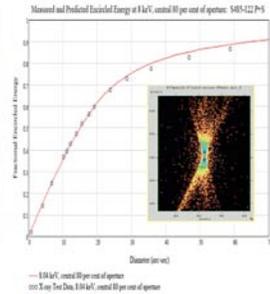
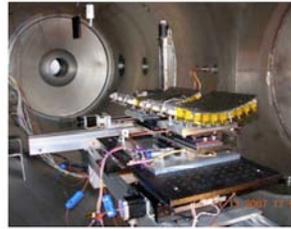
**The thermal glass slumping technology will not only meet the original 15" requirement, but also most likely will be able to achieve the 5" goal.**

Another significant development is the fabrication of "forming mandrels" in a collaborative effort between ASD and the Goddard Engineering Directorate. Up until very recently, forming mandrels only meeting the original 15" requirements were available. In the last six months, this collaborative effort has been able to fabricate for the first time a mandrel that meets the 5" IXO requirement. This mandrel is being used to develop techniques to fabricate mirror segments that will meet the 5" requirement, including the slumping and coating processes.

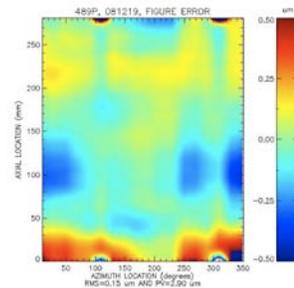
The Nuclear Spectroscopic Telescope Array (NuSTAR) is a Small Explorer under development (Harrison/Caltech, PI). ASD/GSFC is a member of the team, with the responsibility of providing glass mirror substrates using a glass-forming technology that has been developed in the last few years at GSFC by Zhang.



Left: The NuSTAR mirror substrates production facility in Building 22, Room 198. The facility includes clean tents, ovens, and load carts. This chart shows the axial figure quality distribution (arcsec) of the first batch of mirror substrates produced on December 15, 2008. The red dashed line represents the NuSTAR requirement. Credit: NASA/GSFC



Left: The X-ray test chamber in Area 200, where a pair of mirror segments was tested in November 2007. Right: The resulting X-ray image and a graph of the encircled energy fraction vs. diameter for it. Credit: NASA/GSFC



Left: The IXO mandrel is being figured on a polisher in Building 5 at GSFC. Right: A surface contour map of the finished mandrel, which meets IXO requirements for making 5" mirrors. Credit: NASA/GSFC

These substrates will be shipped to the Danish Space Research Institute to be coated with multi-layers to enhance their reflectivity of high-energy (10–80 keV) X-rays. They will then be shipped to Columbia University for alignment and assembly into two mirror modules.

Work began in February 2008 with facility modification and procurement of ovens and other necessary equipment. The work completed on schedule and within budget. The entire mirror substrate production facility, located in Building 22 at Goddard, became fully operational on September 1, 2008. Production preparation work and personnel training took place in the subsequent three and a half months.

The first batch of flight mirror substrates was produced on December 15, 2008, as scheduled. The production will continue until December 2009, when 4,815 mir-

ror substrates (plus 15% spares) will have been delivered.

### GSFC 600-meter X-ray Beamline

The GSFC 600-meter X-ray beamline is located at the Goddard Geophysics and Astronomy Observatory (GGAO) about five miles from Goddard's main campus. It was originally built for technology development associated with the Black Hole Imager (BHI) vision mission, but now also supports optics testing for IXO and Astro-H. Keith Gendreau of the X-ray Astrophysics lab is the beamline's lead scientist.

**Each station of the beamline is powered and has phone and Internet access. The facility can support remote testing control through the Internet links.**

The beamline consists of a 10-inch diameter steel vacuum pipe 600 meters long with three stations. An X-ray source building at one end supports a number of X-ray sources, including Oxford tubes, Manson sources with standard vacuum fittings.

An optics building located 150 meters down the pipe from the X-ray source building has a 1m-class vacuum changer, where X-ray optics or other experiments can be placed in the beam. Another 450 meters down the pipe is a third building containing a 1m × 4m chamber, followed by an X-ray CCD detector.

This longer chamber supports testing of X-ray optics with focal lengths up to 10 meters. The longer chamber is used primarily to support IXO and Astro-H development, but it can also handle sounding rocket payloads.

Each station of the beamline is powered and has phone and Internet access. The facility can support remote testing control through the Internet links. Gendreau and collaborators have obtained X-ray fringes using a grazing-incidence X-ray interferometer in this facility. They have also demonstrated diffraction-limited refractive X-ray optics as well as IXO/Constellation-X X-ray optics.



### Laboratory Development of X-ray Polarimetry

The charge signal associated with the photoelectric absorption of X-rays has been exploited over many years for imaging, timing, and spectroscopy. It has long been recognized that a polarization signature is also present, as the photoelectron direction is correlated with the photon electric-field vector.

Measuring the direction of the photoelectron track in a practical detector is complicated by the fact that the photoelectron track length is small ( $< 10^{-2}$ ) compared to the photon absorption depth. However, Costa et al. (2001) demonstrated that a gas proportional counter with a finely pixelated readout can make polarization measurements in the X-ray band. Careful choices of gas composition and pressure allow tuning of the photoelectric path length; current practical technologies require that the photoelectron track be between 100 and 1000 microns in the band of interest.

Over the last few years, members of the X-ray Astrophysics laboratory (Jahoda, Black, Hill, Deines-Jones, Swank) have concentrated on exploiting photoelectric polarimetry in geometries suitable for Explorer class missions. Initial efforts led to the use of thin-film transistor arrays to create readout planes which could, in principle, be arbitrarily large (Black, 2003; Black et al., 2004) and led to a 2003 SMEX proposal: the Advanced X-ray Polarimeter.

Recent efforts have focused on increasing the efficiency by exploiting a Time Projection Chamber readout (Black et al., 2007). In this geometry, the track is drifted perpendicular to the photon direction of incidence to a readout plane. This innovation decouples detector depth (i.e., efficiency) from the ability to image the track (polarization sensitivity).

The TPC geometry can be adapted to the focal plane of an X-ray optic to study the polarization of faint persistent sources (as is proposed in the Gravitational and Extreme Magnetism SMEX) as well as for the large-area, large-field-of-view detectors that would be required to study polarization from bright transients (Hill et al., 2007).

### Coded-Mask and CdZnTe Detector Development

It is not possible to focus gamma-rays with current technology, so the wide-field Burst Alert Telescope (BAT) on Swift uses a technique called coded-aperture imaging to image and localize incoming gamma-rays. Gamma rays are detected at the focal plane by 32,768 pieces of CZT.

ASD (Barthelmy, Tueller, Okajima) has three development efforts to improve CZT detectors for new mission applications:

- the electronics and packaging for the Proto-EXIST and EXIST missions;
- a strip detector for the InFOCuS balloon instrument;
- and a pixelated detector for homeland security uses.

The proto-EXIST and EXIST effort are described elsewhere.

The CZT strip detector for InFOCuS is a 20-micron 2-D pattern of strips on 2mm CZT. ASD is working with Goddard's Engineering Directorate on this effort for the actual electrode fabrication on the CZT material. This InFOCuS detector is  $26 \times 26 \times 2$ mm

and uses the XA1 ASIC that we have previously used in the pixelated InFOCuS detector and for the Swift-BAT detector array. There is also a parallel effort to use the newer VATAGP7 ASIC from Gamma Medica-IDEAS, Inc.

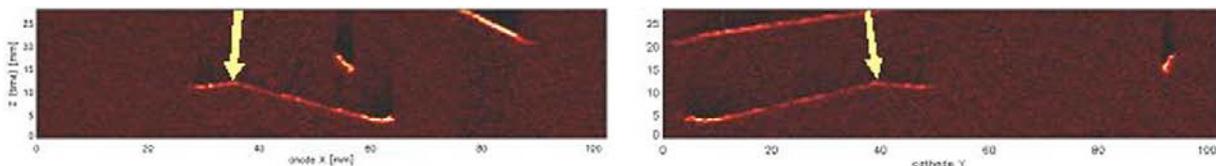
The homeland security effort involves a  $20 \times 20 \times 5$ mm CZT crystal with an  $11 \times 11$  pattern of pixelated electrodes. Takashi Okajima (code 662) is working with the Engineering Directorate on this effort.

### Detectors for Gamma Ray and Neutron Imaging

Stanley Hunter is leading a group that is developing the Three-Dimensional Track Imager (3-DTI) for gamma-ray astronomy. The 3-DTI is a large-volume time-projection chamber (TPC) with two-dimensional micro-well detector (MWD) readout. Each well of the MWD is a gas proportional counter with gain.

The 3-DTI development is motivated by the technology requirements for a future gamma-ray telescope that will provide optimum angular resolution over the energy range from 0.5 to 500 MeV. Gamma-ray imaging, i.e., determination of the photon incident direction, energy, and polarization, is accomplished by tracking the Compton recoil electron or electron-positron pair resulting from photon interactions in the xenon TPC gas.

Beginning in 2007, this group has received funding from the Defense Threat Reduction Agency (DTRA) to extend the 3-DTI technology to imaging of neutrons from passive and active interrogation of special nuclear materials (SNM). The performance goal of the Neutron Imaging Camera (NIC) is to detect small amounts ( $\sim 1$  kg) at moderate (30–50m) stand-off distances in short ( $\sim 5$  minute) integration times.



An example of a  ${}^3\text{He}(n,p)\text{T}$  interaction recorded by the 3-DTI/NIC. The left and right panels show the X-Z and Y-Z projections, respectively, from the 3-DTI. The incident neutron is indicated by the white arrow. The recoil proton (long track) and triton (short track) fragments are clearly seen emanating from the interaction vertex. The other track images are probably elastic scattering of neutrons on  ${}^3\text{He}$  nuclei.

The NIC application replaces the Xe gas in the 3-DTI with  $^3\text{He}$  and tracks the proton and triton fragments resulting from neutron capture on  $^3\text{He}$ ,  $^3\text{He}(n,p)\text{T}$ .

During the last year, the group has built and tested a  $10 \times 10 \times 15 \text{ cm}^3$  3-DTI prototype. This prototype has a  $10 \times 10 \text{ cm}^2$  MWD readout with 512 channels of charge amplifier and transient digitizer electronics. Recently, we have been testing this NIC prototype in a neutron beam at the Naval Surface Warfare Center Carderock Division (NSWC/CD). Analysis of many  $^3\text{He}(n,p)\text{T}$  interactions recorded by the 3-DTI/NIC gives a measure of the device's angular resolution of about 11 degrees. The next phase of this work is to design, build, and test a  $25 \times 25 \times 50 \text{ cm}^3$  prototype of the 3-DTI/NIC.

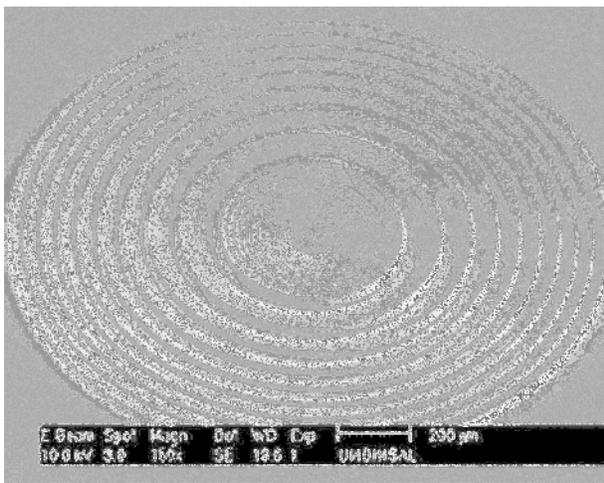
### Phase Fresnel Lens Development for X-ray & Gamma-ray Astronomy

As compared to other wavelengths, astronomical observations in the X-ray and gamma-ray energy regimes have been constrained by limited sensitivity and angular resolution. Diffractive optics, specifically Phase Fresnel Lenses (PFLs) have high throughput at hard x-ray and gamma-ray energies and in principle can achieve diffraction-limited angular resolution, translating into milli-arcsecond to micro-arcsecond imaging in the X-ray and gamma-ray bands. Furthermore, PFLs are capable of being scaled to large, meter-size

dimensions, leading to dramatic improvements in sensitivity.

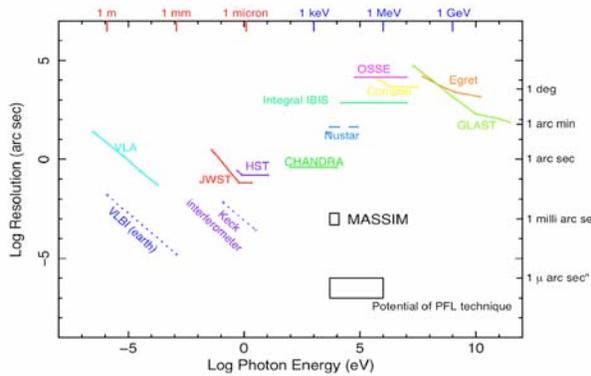
**Advances have been made in overcoming one of the main limitations of purely diffractive optics, the narrow bandwidth within which the superb angular resolution is obtained.**

The fabrication and characterization of the imaging performance of PFLs geared towards astronomical use have been hampered by the inherent long focal lengths and fabrication of macroscopic lenses with the needed micro-feature size. The availability of sufficiently long x-ray beam lines and advances in Micro-Electrical-Mechanical System (MEMS) fabrication techniques have ameliorated these impediments in regards to ground-based performance characterization. Advances in formation-flying spacecraft systems make an eventual mission feasible, and a team of scientists from ASD/GSFC and the University of Maryland are collaborating with the GSFC Guidance, Navigation, and Control (GN&C) Systems Engineering Branch, under a GSFC IRAD award, to further develop the formation-flying aspects. The team includes Krizmanic, Streitmatter, Arzoumanian, Gendreau, and Gehrels at GSFC, and Badilita, Ghodsssi, Morgan and Skinner at Maryland.



A prototype PFL fabricated at the University of Maryland using gray-scale lithography. Credit: Univ. of Maryland

The University of Maryland has employed gray-scaled lithography to fabricate silicon PFLs in a scalable format suitable for astronomical instrumentation, and the team has measured near diffraction-limited performance with high efficiency in focusing 8 keV X-rays at the GSFC 600-meter Interferometry Testbed. The results demonstrate performance approximately a factor of 2 away from the diffraction limit, corresponding to an angular resolution of 25 milli-arcseconds, and with a measured absolute efficiency of 38% at 8 keV, which is 76% of the theoretical maximum that includes absorptive effects. Furthermore, a previously unseen interference effect induced by our specific implementation of these PFLs that is responsible for the reduction in measured efficiency has been observed and characterized. Second generation PFLs have been fabricated and tested at their design energy of 17.4 keV and complete characterization is in progress.



The imaging performance of missions employing PFL-achromats compared to other telescopes. The MASSIM mission is designed to perform milli-arcsecond imaging in the X-ray band. Credit: MASSIM Strategic Concepts Proposal, Gerry Skinner, PI

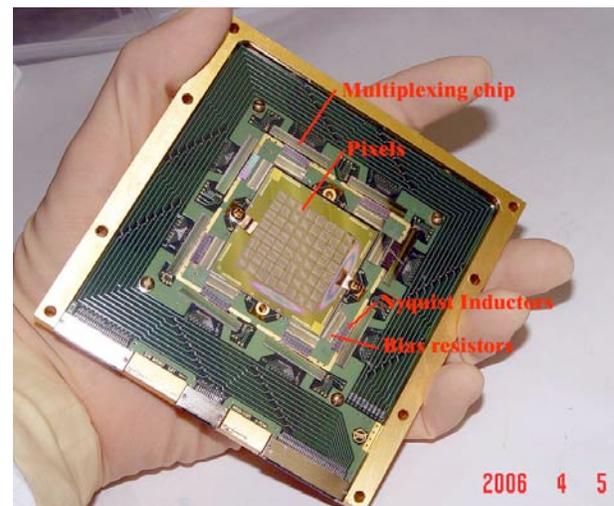
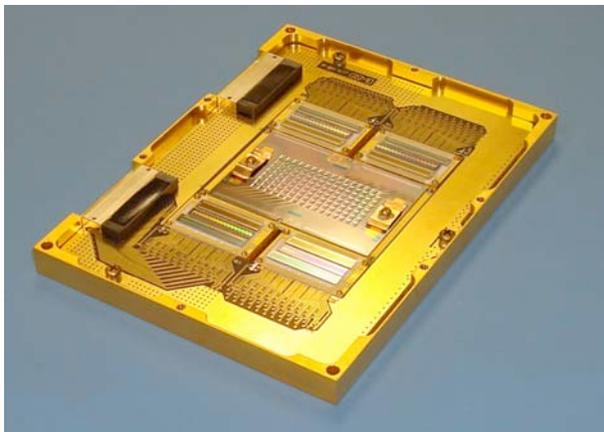
Advances have been made in overcoming one of the main limitations of purely diffractive optics, the narrow bandwidth within which the superb angular resolution is obtained. The solution to this chromaticity problem is obtained by introducing a refractive component along with the PFL to construct an achromat. The refractive component is fabricated at GSFC using diamond turning and initial experiments have used a refractive component to alter the focal length of our 8 keV PFL, bringing the performance closer to the diffraction limit. Experimentation in the near future will incorporate a true achromat and demonstrate near diffraction-limited performance over a much larger energy range as compared to purely diffractive optics. These results will demonstrate the superior im-

aging potential in the x-ray/gamma-ray energy band for PFL-based optics in a format that is scalable for astronomical applications.

### Far-Infrared Detectors

The past decade has seen dramatic advances in many areas of long wavelength astrophysics. WMAP, following the great successes of Cosmic Background Explorer (COBE), has confirmed our general understanding of the early universe and allowed us to quantify critical parameters — its age, composition, and early evolution. Spitzer has provided an extraordinary imaging and mid-infrared spectroscopic capability, which has resulted in an increasingly improving picture of the evolution of galaxies over the life of the universe. Herschel will be launched soon, and will provide our first large-scale look at the high-redshift universe in the submillimeter. JWST, to be launched in a few years, will provide a window into the epoch of galaxy formation to clarify the processes that produced the present universe.

Future far-infrared and millimeter facilities will play an important role in clarifying and extending this work. More than half the power of high-luminosity galaxies is emitted in the rest-frame far infrared, so far infrared and submillimeter imaging and spectroscopy is required for a full understanding of the physics of these systems. The next steps in NASA's profoundly successful science program are currently being developed and the priorities for the space missions, supplemented by suborbital missions, being established.



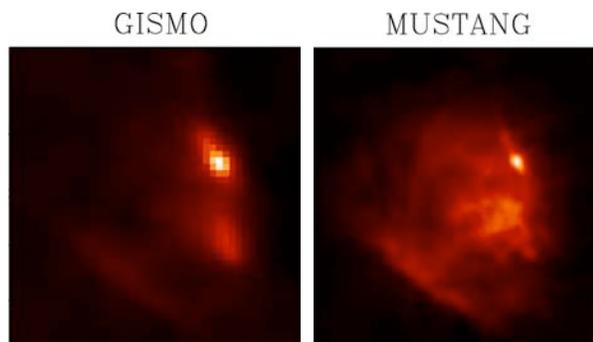
Left: The GISMO detector array. Right: MUSTANG detector array.

SOFIA, now nearing completion, will be a key facility for imaging and spectroscopic follow-up of Spitzer and Herschel discoveries. Measurements of the polarization of the CMB promise to allow us to distinguish among models of the first instants of our universe. Further in the future, great advances in sensitivity, angular resolution, and overall instrument capability will be realized by large cryogenic telescopes in space, such as SAFIR, SPIRIT, and SPECS. High-performance far-infrared detector arrays are required for all this high priority work.

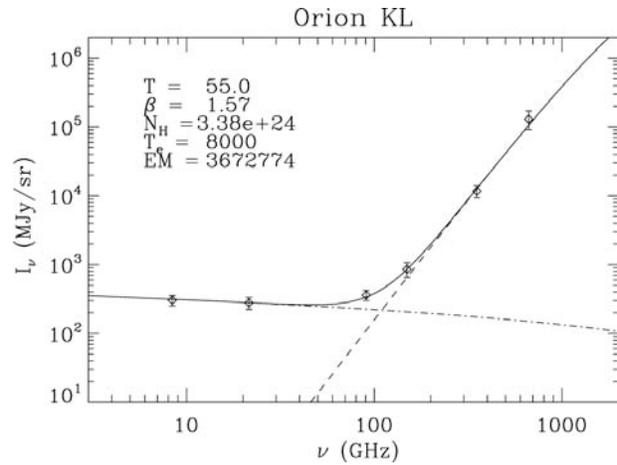
**The far-IR instrument development group's large-format filled arrays will enable major advances in space-borne, sub-orbital, and ground-based infrared, far-infrared and sub-millimeter instrumentation.**

The far-IR instrument development group in ASD (Benford, Chuss, Moseley, Staguhn, Voellmer, Wollack) have ongoing research projects to develop, implement, and field these detector arrays. Our large-format filled arrays will enable major advances in space-borne, sub-orbital, and ground-based infrared, far-infrared and sub-millimeter instrumentation.

One recent success has been the development of a long wavelength (2 mm) camera based on a 128-element close-packed planar bolometer array that uses novel superconducting thermistors read out by SQUID multiplexers. This instrument, named GISMO, has been used for observations on a ground-based telescope, where it has already provided a great advance in



The Orion KL region as viewed by GISMO (left) and MUSTANG (right).



A combined observation using both detectors provided a new measurement of the thermal-to-nonthermal spectral-energy distribution of the Orion nebular region (Dicker et al., in preparation).

our knowledge of the technology and produced new astronomical measurements. Its detector array is designed to be able to scale to 1,280-pixel arrays.

We have also fielded the detector subsystem for the MUSTANG 3 mm camera, a facility instrument at the Green Bank Telescope. Its detector array is smaller and less scalable than GISMO's. However, its observing runs have also produced cutting-edge high-resolution observations at long wavelengths.

### Large-format Bolometer Arrays for Astronomy and Cosmology

The last decade has seen revolutionary increases in the utility of submillimeter and millimeter observations, both for cosmological studies and for large-scale surveys of our galaxy. This increase in scientific performance has resulted in rapid increases in observing speed that have been driven by exponential growth in the performance and size of detector arrays for the  $\lambda > 100 \mu\text{m}$  spectral range.

The detector group in the Observational Cosmology Laboratory (Benford, Chuss, Moseley, and Wollack, with Christine Allen from Engineering) has been centrally involved in the production of high-performance bolometer arrays since the 1980s. In the early 1980s, they developed processes that allowed the fabrication of large arrays of bolometers with performance near theoretical limits. Detector arrays were developed for

use on the Kuiper Airborne Observatory, and later they were provided for applications in submillimeter spectrometers and imagers for use on the Caltech Submillimeter Observatory (CSO) and the James Clerk Maxwell Telescope. These arrays were among the first large arrays to be applied at these wavelengths, and with their first results, showed the promise of large arrays, even with existing facilities.

In the first years of this decade, the GSFC team developed a 12 x 32 detector array for the HAWC facility instrument on SOFIA. The prototype array in this development became the SHARC-II detector for the CSO, where it is a facility instrument, and remains the highest-performance 350  $\mu\text{m}$  receiver in operation.

In the past 4 years, GSFC has transitioned almost completely to transition-edge (superconducting) sensor (TES) detectors and has produced the detector systems for the Atacama Cosmology Telescope (ACT). This instrument, using three 32 x 32 arrays—the largest in use—is in its first year of operation, measuring the small-scale fluctuations in the CMB and Sunyaev-Zeldovich (SZ) effect. The GSFC group has several arrays in the field, where they are demonstrating the detector technology and producing useful science; see the previous section on far-IR detectors for detailed description of these instruments and their scientific results. The success of this development is due to the strong fabrication and test capability of GSFC com-

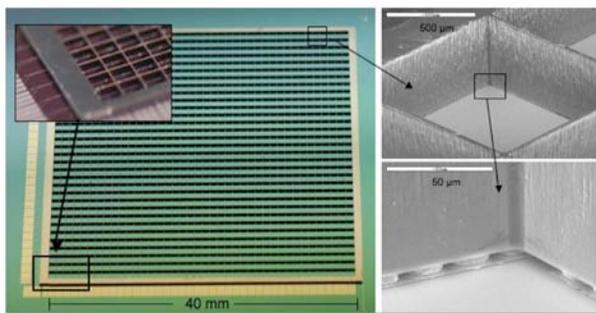
ined with a close collaboration with NIST (Boulder) for SQUID-based amplifiers and multiplexers.

**The success of recent developments is due to the strong fabrication and test capability of GSFC combined with a close collaboration with NIST (Boulder) for SQUID-based amplifiers and multiplexers.**

With the increasing format of the detector arrays, the engineering of the array system is an increasingly large element of the development program. For the past three years, the GSFC team has been developing integrated submillimeter- and millimeter-wavelength arrays based on the NIST SCUBA II 32 x 40 multiplexer. While the SCUBA II instrument is in its early stages of demonstration, the detectors developed for it are not easily modified for low-background applications encountered from space, airborne, and balloon-based imagers and spectrometers. Therefore, the GSFC team is developing versatile arrays that can be optimized for a wide range of backgrounds and wavelengths of operation but that will interface to the SCUBA II multiplexer.

This development relies on a range of capabilities developed at GSFC over the past years: Micromachining of large arrays of 1  $\mu\text{m}$  thick detectors; production of low noise TES thermometers; and the production of interconnections between the detector and its multiplexer using superconducting indium bump bonds.

Most steps required to allow the production of this array are complete. The device has been successfully micromachined and the backshort/absorber array to create the correct electromagnetic conditions for pixel absorption has been demonstrated. The two remaining steps, whose developments are now in progress, are the production of superconducting through-wafer vias and the production of 0.1 K TES thermometers of the correct resistance. The schedule is to have a detector bump bonded to an engineering-grade array by September 2009, with the production of detectors for the PIPER experiment in FY 2010.



Bump-bonding technology is essential for the integration of large arrays to SQUID multiplexers. This figure shows a 32 x 40 dummy array which is bump bonded to a dummy multiplexer. This work builds on a GSFC bump-bonding capability developed in the production of the microshutter arrays for the NIRSpec on JWST. Credit: NASA/GSFC

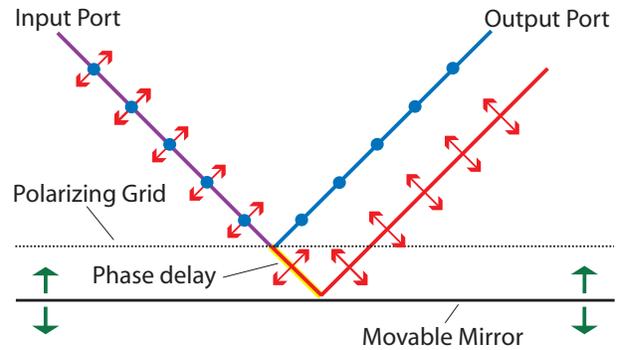
These arrays, which can be produced with quantum efficiency near unity, are expected to be primary research tools for GSFC and our collaborators for several years. We plan to deploy them in the PIPER CMB polarization experiment, SAFIRE on SOFIA, and in a range of ground-based and airborne applications (e.g., a potential upgrade to HAWC). The goal is to strike a balance between development and application that allows rapid progress to be made in CMB studies and far-infrared astronomy, and to be a resource for the wider community.

### Variable-delay Polarization Modulators for Exploring Inflation

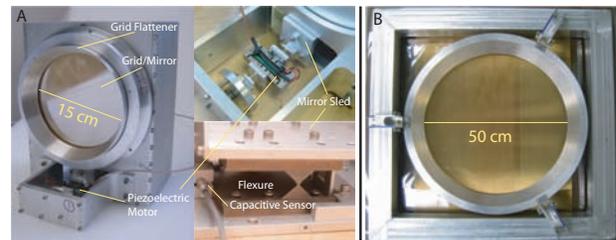
The study of the cosmic microwave background (CMB) with missions such as COBE and WMAP has proven to be one of the most valuable tools in decoding the physics of the early universe. To explain the observed flatness and the origin of structure, it has been hypothesized that the universe underwent an early epoch of exponential expansion known as inflation. If inflation occurred, it is expected to have left a small, polarized signature on the CMB. Measurement of such a signal would provide direct evidence for this inflationary epoch, along with a means by which to measure the physics of the first  $10^{-32}$  second of the universe.

**Measurement of CMB polarization would provide direct evidence for inflation and a means by which to measure the physics of the first  $10^{-32}$  seconds of the universe**

Polarization modulation provides a means for extracting the small polarized signal from inflation from the large unpolarized CMB. To this end, variable-delay polarization modulators (VPMs) are being developed for a space-based instrument to measure the polarization of the CMB by Chuss, Wollack, Moseley, Benford, Hinshaw and Voellmer in the ASD Observational Cosmology Lab. These modulators consist of a polarizing grid placed parallel to and in front of a movable mirror. By varying the grid-mirror separation, the phase between two orthogonal linear polarizations is also varied. This leads to a modulation of a



VPMs consist of a polarizing grid placed parallel to and in front of a movable mirror. By varying the grid-mirror separation, the phase between two orthogonal linear polarizations is also varied.



Left: The submillimeter prototype VPM, constructed for use with the Hertz submillimeter polarimeter. Right: A larger grid for a CMB VPM.

single linear Stokes parameter with little contamination from the instrument.

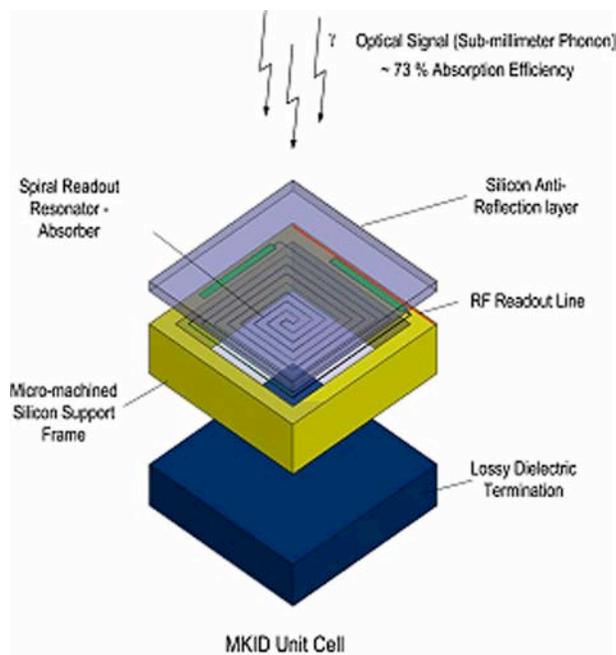
VPMs are potentially well suited for a space mission because they avoid the use of dielectrics that require complex antireflection coatings. The modulation motion can be accomplished using small linear motions that can be done with reliable frictionless flexures. In addition, VPMs can be constructed large enough to cover the primary aperture of the telescope. This is advantageous in that it allows the modulation to be encoded on the signal before it can be contaminated by the instrument.

Prototype VPMs have been constructed for use with the Hertz submillimeter polarimeter. These have been demonstrated at the Submillimeter Telescope Observatory in Arizona. The team is currently working on second generation VPMs for use in two pathfinder systems: PIPER, a funded balloon-borne CMB polarization experiment (PI, Kogut) and POINCARE, a proposed ground-based CMB polarimeter.

## MKID Detectors for Submillimeter Astronomy

Ed Wollack and collaborators are actively pursuing the extension of Microwave Kinetic Inductance Detectors (MKIDs) technology to the 38–400  $\mu\text{m}$  spectral regions via a novel detector concept. Of the high-performance detector-array technologies currently being developed, the MKIDs may have the greatest promise for scaling to very large arrays ( $\sim 10^5$  detectors). Such arrays can provide high quantum efficiency and can be designed to provide background-limited performance over a wide range of incident powers, making them candidates for a wide range of instruments, ranging from suborbital imagers to spaceborne spectrometers.

Such large-format detector technologies are much needed in this important spectral region. Many of the primary diagnostics of a large range of galactic processes require observations in this spectral range. The far-infrared dust emission from normal and ultraluminous galaxies peaks in this spectral range, and its measurements are essential for understanding the energy production mechanisms and processes in the gal-



This sketch shows the sensor topology under study. Photons with energy greater than the gap energy are absorbed in the meander. The quasiparticle excitations change the center frequency and  $Q$  of the 1 GHz stepped-impedance spiral resonator.

axies. Fine-structure lines of O III, NIII, O I, C I, and N II fall in this spectral range. These lines can provide high-quality measurements of elemental abundances and physical conditions in the emitting regions. Many excited states of molecules, such as CO, are seen in this spectral range, and provide the capability to probe physical conditions in hot molecular clouds. Low-lying transitions of hydrides in this spectral region can probe cores of cooling clouds, providing information on star-formation processes. The goal is to produce detectors which will permit the use of these powerful diagnostic tools in future missions.

**Many of the primary diagnostics of a large range of galactic processes require observations in the submillimeter range.**

Presently, MKID detectors employ a resonant tank circuit made from a superconducting transmission line. Its quality factor,  $Q$ , and central frequency are read out using a microwave reflectometer. Millimeter-wave radiation is coupled into the device from an antenna, where it breaks Cooper pairs in the superconductor. This results in a change in the kinetic inductance of the microwave circuit, causing a change in the frequency and  $Q$  of the circuit. This technique works well at frequencies where the radiation can be coupled into the device using antennas and superconducting transmission lines. At frequencies above the superconducting gap of Nb, quality transmission lines are difficult to produce, so a different approach must be adopted. To achieve the desired sensor performance in the desired band, we modify this scheme by choosing the resonator metallization geometry and material properties consistent with its necessary roles in absorption of the incident wave and readout of the detector signal. The incoming light, with photon energy much greater than the superconducting gap, interacts with the spiral microwave transmission line.

In the approach under development, the meander is chosen to have a surface-impedance and filling factor such that it presents the optimal matching impedance to the incoming wave, about  $157 \Omega$  per square. When the optical power is absorbed, it excites quasiparticles in the superconducting spiral, modifying the kinetic inductance of the line. The transmission line is config-

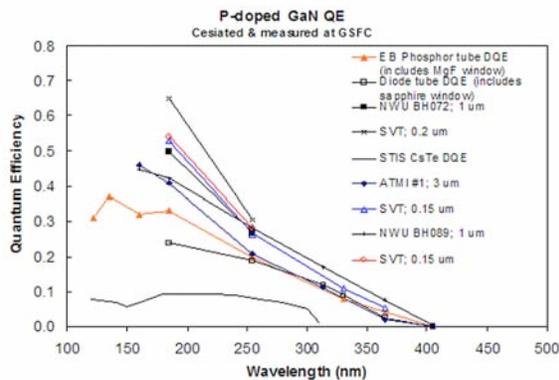
ured as a  $\lambda/2$  stepped impedance resonator, designed to have a resonant frequency of  $\sim 1$  GHz. The Q of the un-illuminated resonator can be controlled by appropriate selection of the coupling Q to the transmission line. The device is optimized for a particular application by choosing the unloaded Q to be equal to the Q caused by quasiparticle dissipation at maximum power. The density of quasiparticles is a measure of our signal, and is sensed by the change in frequency and Q of the readout resonator.

Pending successful laboratory demonstration of the devices, a test of an array will be conducted in a  $350\mu\text{m}$  imager at the Caltech Submillimeter Observatory (CSO). This collaborative effort is led by Edward Wollack and includes S. Harvey Moseley (ASD), and Wen-Ting Hsieh, Thomas Stevenson and Kongpop U-yen of Goddard's Engineering Directorate and Professor Jonas Zmudizian of Caltech.

### Photon Counter Detector Development

Work is on-going in the Exoplanets and Stellar Astrophysics Lab to develop photon-counting detectors for space in the UV, visible and near-IR by Woodgate, Kimble, Rauscher, Norton and Hilton.

For the UV, a new class of photocathodes are under development with higher QEs than were available in the Hubble, FUSE and GALEX era, based on new ternary materials becoming available such as p-doped AlGaIn and MgZnO, in both planar and nano-wire forms. By cesiating GaN, QEs of 50-65% at 180 nm, a factor  $\sim 6$  higher than flown on HST/STIS, have been obtained.



Quantum efficiency versus wavelength for cesiated GaN processed at GSFC.

A GaN photocathode has been transferred into a diode tube with the QE stable for two years, and into an EBCCD imaging tube in collaboration with Rutgers University.

Work continues via ROSES/APRA funding to extend the wavelength range and to obtain higher QEs and compatibility with microchannel plates (MCPs). SBIR programs funded by NASA are also developing silicon MCPs with AlGaIn photocathodes. Woodgate, along with GSFC engineering, university, NIST and commercial partners, plans to build these photocathodes into EBCCD and EBCMOS and MCP detectors.

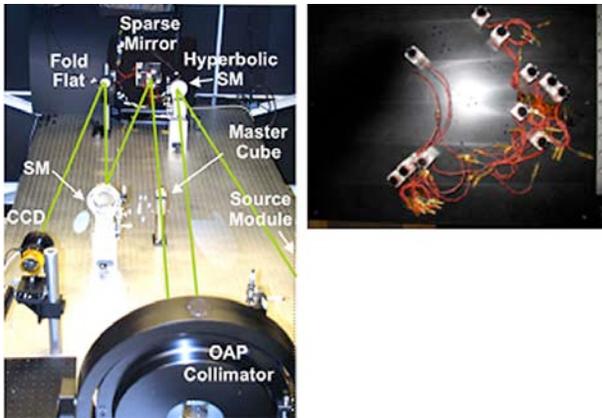
In the visible, photon-counting EMCCDs are being tested for use in future space spectrographs for faint objects such as exoplanet atmospheres, and will use fast controllers to reduce Clock Induced Charge to extend the useful dynamic range of the photon-counting regime.

In the Near-IR the use of InGaAs photocathodes in EBCCD detectors are being investigated, including the extension of useful external QE at cold temperatures for long exposures via an SBIR program.

### Fizeau Interferometry & Synthetic Imaging Formation Flying Testbeds (FIT/SIFFT)

The primary goal of the FIT/SIFFT project is to mature the command and control algorithms required to enable formation-flying sparse-aperture/interferometric imaging missions. These systems must collectively operate over  $\sim 12$  orders of magnitude, from the nanometer to the kilometer scale, and will therefore consist of "staged-control" algorithms operating in smaller, overlapping regimes but operating cooperatively over the full dynamic range.

K. Carpenter (667) is the PI of the effort and key co-investigators include: R. G. Lyon (GSFC), D. Mozurkewich (Seabrook Engineering), D. Miller (MIT), and P. Stahl (MSFC). The GSFC-located FIT is developing and demonstrating closed-loop control, utilizing feedback from the science data, of the tip, tilt, piston, and translation of mirrors in a sparse array and of the overall system to keep beams in phase and to optimize imaging.



Left: FIT Phase 1 Testbed at GSFC, without baffles for clarity. Right: The FIT Phase 2 array plate in assembly, with 11 of 18 mirrors/actuators installed.



SIFFT: SPHERES on the MSFC flat floor (left) and aboard ISS right.

The SIFFT uses the MIT Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) on the Flat Floor facility at MSFC and on the International Space Station (ISS) in Earth orbit to address constellation-wide sensing and control of the formation-flying spacecraft. SIFFT is developing and demonstrating specific algorithms for autonomous precision formation flying and efficient synthetic imaging maneuvers of an array of spacecraft.

The end goal of this research is to combine these two systems into one system that will provide staged-control over the full dynamic range needed to enable these missions. While the detailed design of these testbeds are based on the Stellar Imager (SI) mission, the technologies being advanced will help enable numerous additional missions being considered by NASA for flight, including the Space Infrared Interferometric Telescope (SPIRIT), Sub-Millimeter Probe of the Evolution of Cosmic Structure (SPECS), Life Finder (LF), Black Hole Imager (BHI/MAXIM), and Planet

*On the Web*

Stellar Imager  
[hires.gsfc.nasa.gov/si](http://hires.gsfc.nasa.gov/si)

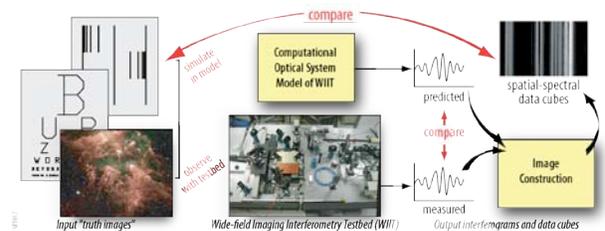
Imager (PI), as well as smaller precursor missions, such as the Fourier Kelvin Stellar Interferometer (FKSI), SI Pathfinder, selected Exo-Planet Probes, and ESA's Pegase.

**Wide-field Imaging Interferometry Testbed**

Leisawitz and Rinehart are developing a broadly-applicable technique for wide field-of-view “double Fourier” (spatial and spectral) interferometry and evaluating its practical limitations. The Space Infrared Interferometric Telescope (SPIRIT; see the Mission Concepts section) could employ this technique — an analogue to integral field spectroscopy — to image stars, planetary systems, and galaxies in the far-IR at 100x better angular resolution than the Spitzer Space Telescope while simultaneously providing information-rich spectra.

In 2008 the Wide-field Imaging Interferometry Testbed was moved from its development lab to a new, state-of-the-art Advanced Interferometry and Metrology (AIM) Lab, a major project milestone. In the AIM Lab, WIIT replicates the functionality and behavior of a space-based interferometer because the data are practically free of environmentally induced errors, such as wavefront distortion due to air turbulence, fluctuations in temperature and humidity, and vibrations.

Funding support for this research comes from the ROSES APRA program. The period of performance runs through FY11, by which time wide-field imaging interferometry will have matured to TRL 6.



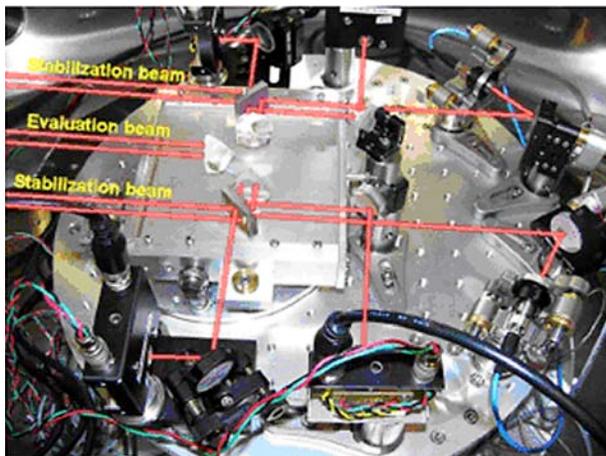
### LISA Testbed: Stabilized Platform Interferometer for LISA Testing

A fundamental issue in the ground testing of LISA interferometry components is the presence of ground noise, both seismic and thermal. LISA interferometric sensitivity is at the picometer level, while ground noise over that timescale is of the order of microns. To provide an environment for testing that is stable over long timescales at the picometer level, Camp and colleagues constructed a stabilized platform testbed.

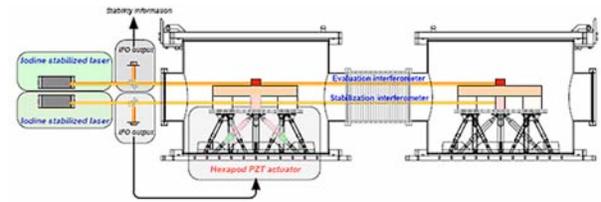
**The stability of the testbed is within a factor of 5 of the LISA requirement.**

Hexapod actuators support platforms separated by one meter, located inside a vacuum system. An iodine stabilized laser system is used to measure the relative motion of the platforms by using optical components to form Michelson interferometers between the platforms.

The Michelson interferometer output is then fed back to a hexapod actuator to stabilize the distance between the platforms. This results in a suppression of relative motion of the platforms, creating an environment which is sufficiently stable for LISA interferometry



Testbed optical components that comprise the Michelson interferometers measure the relative motion of the platforms. They are bonded to a ULE block mounted on each hexapod. Credit: NASA/GSFC



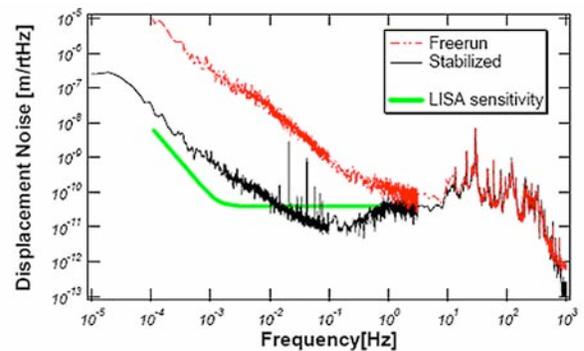
The LISA Testbed uses hexapod actuators to support platforms separated by one meter, located inside a vacuum system. An iodine stabilized laser system measures the relative motion of the platforms by using optical components to form Michelson interferometers between the platforms. Credit: NASA/GSFC

testing. The stability of the system is monitored with an independent stabilized laser.

The stability of the testbed is within a factor of 5 of the LISA requirement of 30 picometer/sqrt(Hz) at 1 mHz. The limiting noise source is cross-coupling of the unstabilized pitch degree of freedom to length, and is under investigation.

In achieving this level of performance, the following noise sources were investigated, all of importance to the LISA interferometry design.

- Optical component bonding stability
- Laser frequency stabilization
- Cross-coupling of multiple degrees of freedom
- Effect of thermal variation on alignment and optical pathlength



This plot shows the closed loop stability of the testbed, within a factor of 5 of the LISA requirements at 1 mHz. Credit: NASA/GSFC

With the testbed stable at the LISA requirements, it can be actuated in a known, precise manner in both length and alignment. Thus it can be used, for example, to test the response of the phasemeter to known phase variations, or to test the response of the optical blocks to known length and alignment variations. It is also envisioned that the testbed will be used to characterize the pointing stability of the steering mirror mechanism, and other LISA system components.

## V. Projects

### *Projects in Operation*

#### The Fermi Gamma-ray Space Telescope

GSFC personnel are extremely active in all aspects of Fermi (formerly the Gamma-ray Large Area Space Telescope, GLAST), both at the mission level and within the instrument teams. Highlighted here is GSFC's role in Fermi's Large Area telescope (LAT), some of the current LAT activities, and some of the mission-level work, including the Science Support Center.

**The ACD.** The Anticoincidence Detector (ACD) subsystem of the LAT was designed, integrated, and tested at Goddard. The segmentation (89 individual scintillating tiles), based on the original idea by Bill Atwood (UCSC), maintains the acceptance at the highest gamma-ray energies, a major advance relative to the EGRET design. The wavelength-shifting fibers were installed into the scintillator tiles at Fermilab, and the front-end electronics chips were designed at SLAC. The tiles are arranged to minimize gaps, and the overall detection efficiency for charged particles is better than 0.9997. Jonathan Ormes, the Goddard Director of Space Sciences at the time, managed the early design efforts. Alex Moiseev is the ACD scientist who had the principal responsibility for the design during all phases, and David Thompson was the subsystem scientist-manager. The successful ACD is due to the work of many people at Goddard and else-



The fully assembled Fermi Anticoincidence Detector prior to thermal blanket installation. Credit: NASA/GSFC

where, and it also provided a good training experience for students.

**Current Fermi LAT Activities.** The LAT Principal Investigator is P. F. Michelson (Stanford). Within the LAT team, throughout the development, GSFC members played key roles. Presently, the major roles include the following: N. Gehrels (Senior Scientist Advisory Committee [SSAC] chair and Publication Board [PB] member); A. Harding (Galactic Sources Group coordinator), E. Hays (Spectral Analysis Study group lead), J. McEnery (Analysis Coordinator, SSAC, PB, GRB commissioner); A. Moiseev (active in electron analysis); S. Ritz (Deputy PI, SSAC, PB); D. J. Thompson (Multiwavelength Coordinator, Catalog Group coordinator, SSAC). Band, Bonnell, Cillis, Corbet, Davis, Ferrara, Hirayama, Hunter, Sambruna, Shrader, and Stecker are affiliated-scientist members of the LAT team.

The current PhD students are T. Johnson and W. Micaville (both at University of Maryland), and the post-docs are O. Celia, T. Cheung, and V. Vasileiou. ASD's data analysis has been to work directly with the international team, rather than to define "Goddard" analyses. This has been very successful. Leading by example has helped to foster a strong and productive collaboration, and GSFC personnel have played central roles in most of the major LAT science results thus far.

**Fermi Mission and SSC.** The Fermi mission is managed at Goddard, and the Mission Operations Center (MOC) is located here. Ritz is the Project Scientist, and McEnery, Thompson, and Gehrels are Deputy Project Scientists. Alice Harding and Liz Hayes play key roles in data analysis and theoretical interpretation of Fermi observations. The Fermi Science Support Center (FSSC) is also located at Goddard and is led by C. Shrader. The FSSC functions can be divided into three main roles.

- The mission planning and operations branch compiles and optimizes the Fermi observation plan (including responding to and evaluating Target of Opportunity requests). This branch runs weekly planning meetings to coordinate observatory operations across all mission elements.

- The analysis software and databases branch developed the high-level analysis software in partnership with the LAT and Gamma-ray Burst Monitor (GBM) instrument teams. Extensive testing, both internally and in “beta” tests by members of the Fermi Users Group, was performed. The FSSC also serves data to the community, working with the HEASARC to ensure that the analysis tools and data formats conform to standards in high-energy astrophysics. All data servers are up and running; high-level LAT data and all GBM data are currently publicly available; the portal to the low-level LAT data is currently being used and tested by the LAT instrument team and will be made publicly available in fall 2009, per the mission timeline.
- The user-support branch of the FSSC is responsible for running the Fermi guest investigator program, developing proposal preparation tools, providing documentation, running workshops, and answering questions via an electronic helpdesk. Last year’s Cycle 1 was very successful, and the Cycle 2 proposal deadline is March 6, 2009.

Supporting all three branches of the FSSC is a group of talented programmers and software engineers who build and maintain the software infrastructure and web pages. The MOC is staffed by an outstanding Flight Operations Team and is supported by a small sustaining engineering group. All the mission elements are functioning together efficiently and seamlessly.

### WMAP Operations and Status

WMAP launched from Cape Canaveral on June 30, 2001, aboard a Delta II rocket. From launch to orbit about the second Lagrange point (L2), WMAP mission operations have been extremely smooth and reliable. WMAP continuously surveys the sky in a compound spin and precession that generates the desired scan pattern. There are no pointed observations. Planning is required for about four station-keeping maneuvers per year. Data are downlinked to the Deep Space Network and then relayed to the WMAP Science and Mission Operations Center (SMOC) at Goddard. The down-link contacts allow for real-time checks of health and safety. The SMOC runs Level-0 processing,

then data are transferred to the Science Team, which runs its own checks.

There have been six unplanned interruptions to survey operations. The failure of a single battery cell caused one interruption early in the mission. High-energy charged particles caused three single-event upsets, and the spacecraft was returned to normal survey operations soon after each. Operations were recently interrupted because a transponder became intermittent; the alternate transponder is now used.

**The spring 2008 review approved two additional years of flight operations through the end of FY10, which would produce a total of nine years of data.**

There is no significant degradation anywhere on the observatory. WMAP is passively cooled; there is no cryogen-related lifetime limitation. Of the  $\sim 50$  kg of remaining fuel, a typical station-keeping maneuver requires only  $\sim 0.5$  kg. Fuel is not a limitation to the lifetime of the mission.

Solar eclipse shadows were forecast for October 2007 and January 2008. After careful planning and peer-review, we executed a maneuver to avoid these eclipses. This was the largest maneuver since the early mission and it went smoothly.

As of January 2009, WMAP has been in orbit for 7.5 years and is still taking data at L2. With additional data, WMAP will enable significant science advances in a number of areas. These include:

- a more accurate determination of the density of dark matter;
- a more accurate determination of the amplitude of primordial fluctuations;
- improved constraints on neutrino properties;
- a more detailed characterization of reionization;
- improved sensitivity to gravitational waves, including the ability to rule out the popular  $m^2\phi^2$  theory of inflation;

- the ability to determine whether claimed non-Gaussianity is statistically significant;
- improved models of Galactic foregrounds, which will be vital for Planck and other experiments that look for gravitational waves; and
- improved measurements of microwave emission from planets and from Galactic and extragalactic sources.

The WMAP program is reviewed every two years by the Headquarters Senior Review of operating astrophysics missions. The last review, in spring 2008, approved two additional years of flight operations through the end of FY10, which would produce a total of nine years of data. The project will return to the next Senior Review, in spring 2010, to request additional data analysis funding to release the final data products.

### The Rossi X-ray Timing Explorer

The Rossi X-ray Timing Explorer (RXTE) celebrated its birthday on Dec. 30, 2008, and began its 13th cycle of observations. Jean Swank is the Project Scientist and Tod Strohmayer became the Deputy Project Scientist in 2006. In its long and productive history, RXTE is responsible for numerous discoveries resulting in three Rossi Prizes—to Strohmayer and Chakrabarty (2006), Kouveliotou (2003) and Bradt and Swank (1999)—more than 80 PhD theses and over 1,600 refereed publications.

The observation planning, instrument monitoring, and calibration updates are carried out with the part-time contributions of an experienced team (including Keith Jahoda, Craig Markwardt, and Nikolai Shaposhnikov at Goddard). Improvements in background determination and response matrices continue to be made.

The Science Operations Center (SOC), with Frank Marshall as director, assisted by Robin Corbet as Science Operations Facility manager, and the GSFC Mission Operations group have worked together to continue to automate operations and reduce manpower and expenditures, while preserving RXTE's ability to accommodate new information about targets of opportunity (TOOs) (implemented by SOF personnel

Evan Smith and Divya Pereira). RXTE's most-used follow-up capability is currently for time-scales of 1–2 days. It is possible to have follow-up observations within hours for a select subset of requests, but transients that harbor millisecond pulsars, active periods of magnetars, the lifecycles of galactic black hole transients, and, of course, the active periods of blazars require a response on the order of days that is sustained for days to weeks. RXTE remains the mission that is requested to carry out these observations.

The RXTE project has submitted proposals to each of NASA's Senior Reviews of the Astrophysics Operating Missions since 1994. The 2006 review confirmed RXTE's operations through the 2008 review, by which time the project had developed a program to extend operations through February 2009. The 2008 review concluded that funds were not available for further funding of the longest operating of the competed astrophysics missions. However, continued reductions in operating costs have allowed cycle 13 to extend through September 2009 and possibly further. The possibility of extension of RXTE's mission for an additional year is being explored. This will allow the torch of X-ray coverage of variable sources to be passed to other missions (MAXI, Astrosat).

**Continued reductions in operating costs have allowed RXTE's cycle 13 to extend through—and possibly beyond—September 2009.**

RXTE's repeated observations of targets have resulted in discoveries related to phenomena that are relatively rare. A program of monitoring pulsar spin history resulted in the discovery of magnetar-like behavior in the young pulsar PSR J1846–0258 in Kes 75 (by post-doctoral fellow Fotis Gavriil). Low-mass binaries monitored for changes in the quasi-periodic oscillations (QPO) were found to have intervals of coherent oscillations (Aqu X-1, SAX J1748.9–2012 in NGC 6440, HETE J1900.1–2455). Coverage of the QPO and spectra of multiple Galactic black holes allows the correlations to be related to fundamental properties of mass and spin (as by postdoctoral researcher Nikolai Shaposhnikov). RXTE's observing flexibility

means that it can provide X-ray coverage of gamma-ray transients that Fermi finds active (e.g., 3C 454.3, 3C 66A).

### XMM-Newton Guest Observer Facility

ASD operates the U.S. XMM-Newton Guest Observer Facility (GOF). ESA has allocated resources to support European XMM-Newton users, but has looked to the U.S. GOF to provide support to the large U.S. community. GOF activities include facilitating the submission of GO proposals to ESA and the supplying of expertise, analysis software, documentation, new data products, and access to the data, including both the distribution of proprietary data to PIs and to the full public science archive. The GOF organizes the GO budget submission and review process and manages the distribution of awarded funds.

**Direct comparison of Chandra and XMM-Newton results on clusters of galaxies has revealed a previously unknown error in the Chandra calibration that has major implications for cosmology.**

A U.S. XMM-Newton Users Group under the chairmanship of Mission Scientist Richard Griffiths (Carnegie Mellon University, CMU) provides community oversight of GOF activities. Richard Mushotzky is the NASA Project Scientist for XMM. The XMM-Newton GOF works in conjunction with the GSFC GOFs of other high-energy astrophysics missions (e.g., RXTE, Integral, Swift, and Suzaku) to lower costs and to ensure consistency in the areas of the budget proposal process, FITS tools, database structure, web pages and archival access. Cost savings are leveraged by sharing resources, techniques, expertise, and reusing software.

GOF activities cover a very wide range of endeavors in support of XMM-Newton, and include the following: science analysis software support, development of software tools (QuickSim, Xsim, PIMMS, and update of HEASARC multi-mission software (Browse, etc.)) to support XMM. The GOF created and maintains

the extensively used “ABC Guide” for the analysis of XMM-Newton science data.

#### *On the Web*

The XMM-Newton Guest Observer Facility  
[xmm.gsfc.nasa.gov](http://xmm.gsfc.nasa.gov)

The GOF is involved in the cross-calibration between the XMM-Newton instruments and other X-ray observatories (e.g., Chandra, Suzaku, ASCA, and ROSAT), which enhances the utility of multi-observatory data analysis. This has been a major activity the last two years, with major XMM-Newton GOF participation in the International Astronomical Consortium for High Energy Calibration (IACHEC). It is now becoming clear, thanks to the efforts of the XMM-Newton SOC at the European Space Astronomy Center (ESAC) and the GOF, that the XMM-Newton calibration has become very reliable and that direct comparison of Chandra and XMM-Newton results on clusters of galaxies has revealed a previously unknown error in the Chandra calibration that has major implications for cosmology (Snowden et al., 2008).

The GOF has prepared an Optical Monitor (OM) source catalog (Kuntz et al., 2008, in press) to compliment the X-ray source catalog produced by the XMM-Newton Survey Science Centre (SSC). The database contains entries for every source detected in OM observations. The GOF worked with the STScI to make the OM catalog and data available through the Multimission Archive at Space Telescope (MAST), considerably increasing the data availability to optical astronomers.

The XMM-Newton archive at the GSFC GOF mirrors all public data in the ESA XMM-Newton Science Archive (XSA) at the SOC, as well as proprietary data for U.S. PIs. This mirroring of the data reduces the high data load at the European Space Operations Center site, and provides a much faster data-transfer rate within North America, as well as allowing use of the unique capabilities of the BROWSE database.

The GOF consists of Project Scientist Mushotzky and about nine other support scientists and programmers.

The scientific return to the community is exceptionally high for such a lean staff.

### Swift

Swift is a NASA Explorer mission, with international participation, that is designed to find gamma-ray bursts, and study them over a wide range of wavelengths from gamma-rays to optical light. It was launched in 2004 and is in its extended mission phase with re-entry in 2020.

Gamma-ray bursts (GRBs) are the most powerful explosions the universe has seen since the Big Bang. They come from all directions in the sky and last from a few milliseconds to a few hundred seconds. GRBs are believed to occur in the collapse of some massive stars into supernovae or when two neutron stars merge. However, the details of how such intense pulses of radiation are produced are still not well understood.

To observe GRBs, Swift has three telescopes onboard. The Burst Alert Telescope is a coded-aperture gamma-ray detector that operates between 15 and 150 keV. It detects gamma-ray bursts and rapidly localizes them to approximately three arcminutes. Once this has happened the spacecraft slews (usually within one minute) to point its two narrow-field instruments at the burst. The X-Ray Telescope measures the 0.2–10 keV X-ray flux from the GRB's afterglow and localizes the source to within five arcseconds. The Ultraviolet/Optical telescope collects data between 1600 and 6000 Angstroms and provides a sub-arcsecond position for the burst. Swift distributes these positions for each GRB to other observatories within seconds of obtaining them.

In the four years since launch, Swift has detected and localized approximately 400 GRBs. Some of the mission's key scientific accomplishments have been:

- Finding afterglows for short, hard GRBs and determining that the short, hard GRB 050509B occurred in an elliptical galaxy. This provided support for the theory that short, hard bursts are due to the merging of binary neutron stars and not the collapse of massive stars.
- Detecting GRB 080913A, the most distant known GRB with a redshift of 6.7. This burst occurred when the universe was only one billion years old.
- Observing GRB 080319B, a GRB with an afterglow that was bright enough to see with the naked eye from a dark site.
- Compiling X-ray light curves of several hundred Swift GRBs, which led to a canonical X-ray light curve for afterglows, and has provided much new information on the nature of the central engine.

Swift is a powerful transient observatory that is increasingly being used for non-GRB science. Currently about half the papers on Swift findings are from non-GRB fields, and the fraction is growing. A few examples include: observing more than 300 targets of opportunity per year; making multiwavelength observations of comets, stellar flares, CVs and novae; obtaining 70 ultraviolet light curves of all classes of supernovae; observing galactic transients and AGNs; and undertaking the most sensitive all-sky hard X-ray survey yet performed.

**Currently about half the papers on Swift findings are from non-GRB fields, and the fraction is growing.**

Swift has been widely recognized as a ground-breaking mission. Swift was ranked first in the 2008 Senior Review. PI Neil Gehrels and the Swift Team won the 2007 Rossi Prize, and GRB 080319B (the naked-eye gamma-ray burst) was named one of the top ten science news stories of 2008 by the American Institute of Physics.

The Swift mission has a Guest Investigator Program that is open to the world astrophysics community. In 2008, Swift awarded 780 hours of observing time and 1.8 million dollars in research funds to guest observers. The oversubscription rate has been growing and was more than 4 during Cycle 4. Swift also has an open target of opportunity program. These observations are often made within 24 hours of being requested and can be made within 30 minutes.

### Suzaku (Astro-E2)

Suzaku (Astro-E2) is the fifth in a series of Japanese X-ray astronomy satellites, launched by the Japan Aerospace Exploration Agency (JAXA) on July 10, 2005.

Like ASCA before it, Suzaku is a joint Japanese-U.S. mission, developed by the Institute of Space and Astronautical Science of JAXA (ISAS/JAXA) in collaboration with GSFC and many other institutions.

Suzaku's scientific payload includes three co-aligned instruments, of which two are functional. The X-ray Imaging Spectrometer (XIS) consists of four imaging CCD cameras, three of which are front illuminated (FI: energy range 0.4–12 keV) and one back illuminated (BI: energy range 0.2–12 keV). Each XIS is located at the focal plane of a dedicated X-ray telescope (XRT). The second functional instrument is a nonimaging collimated Hard X-ray Detector (HXD) sensitive in the 10–600 keV band. The third instrument, the X-Ray Spectrometer (XRS), ceased operation shortly after launch due to a spacecraft design error.

GSFC's role includes supplying the XRTs and the XRS "insert" (detector, adiabatic demagnetization refrigerator and LHe cooler), development of data processing software, operation of the U.S. Guest Observer Facility, and administration of the U.S. Guest Observer Program. Rob Petre is the NASA Project Scientist and Lorella Angelini is the Deputy Project Scientist.

The XIS and HXD are healthy and stable, and have produced an abundance of data from a wide variety of cosmic X-ray sources. Key unique Suzaku observations include: measurement of cluster properties beyond their virial radius; broadband measurements of AGN revealing simultaneously complex absorption, a relativistically broadened Fe K line, and a reflection continuum to 20–40 keV; determination of the spin of Galactic black holes and the radius of accreting neutron stars using their relativistically broadened Fe line; and hard X-ray sensitivity sufficient to measure the spectrum of each of the hundreds of AGN detected by Swift.

U.S. observers have access to 50% of the observing time (including 12% through joint Japan/U.S. observations), as well as access to all archival data. In the third observing cycle (April 2008–March 2009) Long Proposals (observing time > 300 ks) were introduced to the program. In the current observing cycle, key projects (observing time > 1Ms) were introduced. Also, joint Suzaku-Chandra observations will become available through the Chandra GO program, and we

are making arrangements for collaborative programs with other missions (Swift, Fermi).

Suzaku received a high ranking (fourth, of nine missions) from the 2008 NASA Senior Review of operating missions. Funding is secure through FY2011, and the opportunity exists to extend U.S. participation through a proposal to the 2010 Senior Review. The most substantial issue arising from the Senior Review is that Guest Observer funding has been reduced to a token level: roughly \$500,000 per year, or \$8,000–\$10,000 per successful proposal.

**Joint Suzaku-Chandra observations will become available through the Chandra GO program, and we are making arrangements for collaborative programs with other missions (Swift, Fermi).**

The Suzaku GOF is responsible for: processing and archiving of the full mission data set and distribution of data to U.S. GOs; development and maintenance of proposal and observation planning tools and documentation; maintaining the calibration database; supporting proposal reviews; assisting GOs analyze data; and ensuring grant funds are distributed in a timely way. The GOF staff consists of three full-time scientists (Koji Mukai, Kenji Hamaguchi, Katja Pottschmidt) and one programmer, plus part-time support from HEASARC staff.

## INTEGRAL

INTEGRAL, the INTErnational Gamma-Ray Astrophysics Laboratory, is an ESA mission for which NASA has been a partner since its selection in 1995. It was launched in October 2002 and has now completed more than six years of successful scientific operations.

INTEGRAL carries two main instruments—the high-resolution gamma-ray spectrometer, SPI, and the high-angular-resolution gamma-ray imager, IBIS—as well as X-ray and optical monitors. Together, these instruments provide unprecedented spectral coverage from the optical to gamma-ray energies up to 10 MeV

as well as excellent imaging capabilities at hard X-ray and gamma-ray energies.

The scientific goals of the INTEGRAL mission are varied and far-reaching. The SPI instrument is a coded-mask germanium spectrometer with excellent energy resolution in the low-energy gamma-ray regime, from 20 keV to 8 MeV. It was designed to study, in detail, gamma-ray lines produced through a variety of processes. These include the decay of radioactive isotopes produced in supernovae and novae as well as the annihilation of positrons near the center of our Galaxy. SPI can trace the production of these radioactive isotopes and positrons by mapping the locations and intensities of the resulting gamma-rays. These studies lead to a better understanding of the chemical evolution of the Galaxy, Galactic star formation rates, and the inner workings of supernovae and novae.

The IBIS imager is a coded-mask gamma-ray telescope that operates between 15 keV and 10 MeV. The sensitivity and angular resolution of this telescope makes it extremely useful for observing Galactic black hole and neutron star binary systems as well as active galactic nuclei (AGN). To this end, a significant portion of the INTEGRAL observing time has been spent scanning the Galactic disk and Galactic Center region in an effort to monitor the known Galactic X-ray binary population and discover new sources. Studies of these binary systems give us a better understanding of the end products of stellar evolution.

In the six years since launch, there have been numerous notable discoveries, including:

- Discovery that the Galactic 511 keV emission due to positron annihilation is not symmetric about the Galactic Center. This has significant implications for determining which source(s) are producing these positrons.
- Observations of the gamma-ray lines from the decay of both  $^{26}\text{Al}$  and  $^{60}\text{Fe}$  in the Galaxy suggest that much of the  $^{26}\text{Al}$  is produced in core-collapse supernovae.
- Discovery of a large number of X-ray binary systems containing a super-giant companion. Among this class of objects, two subclasses have been identified: systems with highly absorbed soft

X-ray spectra and systems that exhibit very fast transient behavior. The hard X-ray sensitivity of IBIS and its monitoring observing program were instrumental for these discoveries.

Since launch, INTEGRAL has operated as an international observatory with observing time available to U.S. scientists. NASA has an INTEGRAL Guest Investigator Program that provides funding for U.S. scientists who were successful in obtaining observing time. In 2008, the INTEGRAL Guest Investigator Program has funded 24 observing programs for a total of \$450,000.

The US INTEGRAL Guest Observer Facility maintains a copy of the full INTEGRAL public data archive and supports U.S. scientists with their data analysis. Neil Gehrels is the NASA INTEGRAL Project Scientist.

### Hubble Space Telescope: SM4 and Wide Field Camera 3

The Hubble Space Telescope Program (HSTP) resides at Goddard. This organization has overall responsibility within NASA for the technical, scientific, and programmatic management of the observatory. The responsibilities of HSTP include operation of the Hubble observatory, both through spacecraft engineering and the implementation of Hubble's science



GSFC personnel completed integration of Wide Field Camera 3 in early 2008. The instrument successfully underwent a comprehensive environmental test program and now awaits launch. Credit: NASA/GSFC

program with the Space Telescope Science Institute (STScI). We develop all new hardware that astronauts will install on Hubble during servicing missions, including new scientific instruments, tools used by the astronauts, and hardware carriers designed to deliver equipment to orbit in the space shuttle's payload bay. Finally, we work with NASA's Johnson Space Center (JSC) to develop the detailed choreography of each Hubble servicing mission.

Five scientists in ASD provide essentially full-time support to the HSTP: Senior Project Scientist David Leckrone; Deputy Senior Project Scientist Mal Niedner; Project Scientist for HST Development Randy Kimble; Project Scientist for HST Operations Ken Carpenter; and Associate Senior Project Scientist Stephen Rinehart. At the highest level, the overarching function of the HST Project Science staff is to assure that Hubble continually meets its scientific performance requirements and remains at the forefront of research..

Servicing Mission 4 (SM4) will be the fifth—and, in all likelihood, the last—shuttle servicing mission to Hubble. SM4 is currently scheduled for May 12, 2009. The HST Project Scientists are continuously and deeply engaged in the development, planning, and training for the servicing mission. One important function is the assignment of mission priorities and the development of response plans for a large suite of possible contingencies during the mission. The payload manifest for SM4 consists of the following (in order of priority): gyroscopes (RSUs); Wide Field Camera 3 (WFC3); replacement instrument computer (SIC&DH-R); Cosmic Origins Spectrograph (COS); batteries; repair of either the Advanced Camera for Surveys (ACS-R) or the Space Telescope Imaging Spectrograph (STIS-R); a replacement Fine Guidance Sensor (FGS2-R), other required instrument repairs; and selected enhancement of spacecraft insulation blankets (NOBLs).

The project scientists have important, well defined roles during the mission itself. Leckrone and Kimble will be part of the HSTP mission team at JSC, while Niedner, Carpenter and Rinehart will work with the SM4 operations team at Goddard. During the 12-hour orbit (EVA) shifts, they will continuously monitor the progress being made by the astronauts in orbit. They

participate as full members of the SM4 mission team in responding to any contingencies that may arise. The insertion of each payload element or the completion of each instrument repair culminates in “aliveness” and “functional” tests to provide an initial assessment of its viability. The project scientists at both Goddard and JSC are heavily involved in these tests. In the case of the new and repaired instruments they are responsible for assessing whether or not the tests resulted in a conclusion of “pass” or “fail.”

**Following a successful Pre-Ship Review that certified WFC3's flight readiness, the instrument was shipped to KSC and inserted into its carrier in preparation for SM4.**

With the insertion of WFC3 and COS—and the expected repair of two heavily used instruments already onboard Hubble—ACS and STIS—both of which failed due to power supply problems, Hubble will be more powerful than ever before. The replacement of key spacecraft components—gyros, batteries, instrument computer and fine guidance sensor—should extend Hubble's operational life by an additional 5–10 years.

Randy Kimble also serves as the Lead Instrument Scientist for the Hubble's new Wide Field Camera 3, which is a powerful general-purpose imager, covering wavelengths from the near ultraviolet to the near infrared. WFC3's UV/VISible (UVIS) channel covers the 200–1000 nm range with a 4K × 4K pixel mosaic of UV-enhanced, low-noise CCDs. Beautifully complementary to the I-band-optimized Wide Field Channel of ACS, WFC3's UVIS channel is particularly powerful in the near-UV (200–400 nm) range, where it offers survey speeds 30 to 100 times those of previous imagers. This capability will be particularly well suited to study, for example, the recent star formation history of nearby galaxies. The IR channel (850–1700 nm), which utilizes a novel HgCdTe focal-plane array custom-developed for WFC3, similarly provides a powerful upgrade from Hubble's current infrared camera, NICMOS. WFC3's superior sensitivity and larger field of view combine to yield a survey speed increase of more than 20 percent, which will be invaluable for



This GALEX image of the variable star Mira extends across more than 3 degrees and shows—for the first time—a tail that trails at least 13 light-years behind the star. Credit: NASA/GALEX.

studies of high-redshift galaxies in the early universe and for continued investigation of dark energy.

The GSFC Detector Characterization Laboratory, which is jointly staffed and managed by ASD and GSFC's Engineering Directorate, has provided invaluable support to the development and characterization of candidate focal plane arrays for the instrument, selection of the flight units, and investigation of subtle detector behaviors for optimizing the interpretation of detector data in flight.

Following delivery of the final flight detector assemblies from Ball Aerospace in late 2007, GSFC personnel completed integration of the instrument in early 2008. In flight configuration, the instrument successfully underwent a comprehensive environmental test program (acoustics, EMI/EMC, thermal-vacuum) in the first half of 2008. The thermal-vacuum test included a thorough science calibration to acquire the necessary performance data to support the on-orbit observing program. Following a successful Pre-Ship Review that certified the flight readiness of the instrument, WFC3 was shipped to KSC, where it was inserted into its launch carrier in preparation for SM4. WFC3 remains in this configuration awaiting launch and the start of its eagerly anticipated scientific operations.

### The Galaxy Evolution Explorer

The Galaxy Evolution Explorer (GALEX), a Small Explorer (SMEX) ultraviolet survey mission, is in its sixth year of science operations. All flight and ground systems are currently healthy.

Most of the GALEX science team and most of the science operations are at Caltech. Approximately one-

third of GALEX observing time is dedicated to a robust Guest Investigator program, operated by GSFC (30 to 35 GI programs annually). Susan Neff (ASD) is the GALEX Mission Scientist.

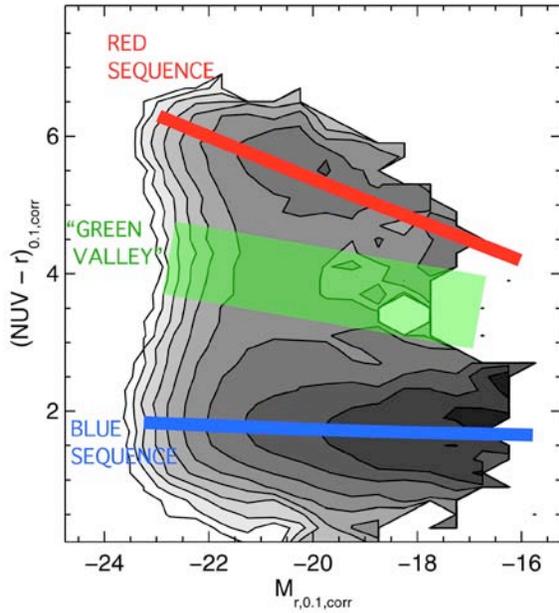
#### *On the Web:*

GALEX publications  
[www.galex.caltech.edu/researcher/data.html](http://www.galex.caltech.edu/researcher/data.html)

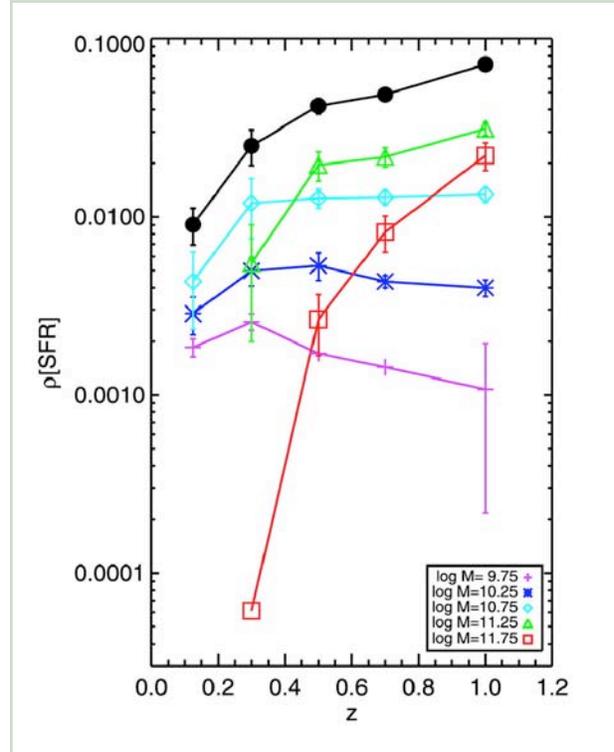
GALEX is in the process of delivering its fifth (annual) GALEX Data Release (GR5) to MAST (Multi-Mission Archive at Space Telescope), which serves both GRs and GI data to the scientific community. GALEX is primarily a survey instrument, designed to obtain large, homogeneous imaging samples in two bandpasses (Far-UV, 1350–1800Å, and Near-UV, 1800–2800Å) that are sensitive tracers of recent star formation. The resulting samples are cross-matched with wide and deep surveys at other wavelengths; a particularly rich match is with the Sloan Digital Sky Survey. GALEX also can provide wide-field, low-resolution spectroscopy, useful, e.g., for identifying HST/COS targets.

The primary GALEX mission (completed in late 2006) had the goals:

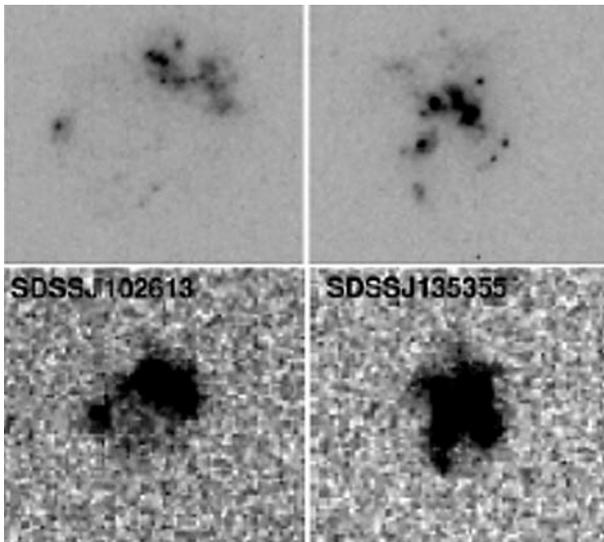
- Calibrate UV observables to star formation rate (SFR);
- Measure star-formation history ( $0 < z < 1.5$ );
- Explore the UV universe.



The UV-optical color-magnitude diagram (UVOCMD) is a powerful tool for separating and relating galaxy types, properties, and evolutionary histories. GALEX UVOCMDs first identified the tendency of AGN to occur preferentially in the “green valley.”



SFR density as a function of redshift, separated by galaxy stellar mass, over the range  $0 < z < 1.2$ .



HST images of GALEX-discovered compact UVLGs reveal that they represent a complex merger of multiple, lower-mass, gas-rich subunits that echo the morphology and physical properties of high- $z$  LBGs. Top row: HST images. Bottom row: The same images artificially redshifted to  $z \sim 3$ , where morphology is uncertain.

The GALEX Extended Mission (EM), endorsed by the 2006 and 2008 Senior Reviews, is carrying out several Legacy Surveys designed to: extend the UV/SFR calibration to low-mass, low-metallicity, and transitional galaxies; relate star-formation history to environment, mass, halo mass, assembly history, and star-formation regime; determine the primary drivers of SF history (by linking SF history to halo mass and assembly history, environment, AGN and their evolution, and the intergalactic medium).

GALEX observations have been used to determine the cosmic star-formation (SF) history in the nearby universe. The standard model of hierarchical structure formation predicts that large structures grow late. However, GALEX results clearly show that while SF occurred in massive galaxies over the period  $1 < z < 4$ , after that it moved to less and less massive hosts (Martin et al., 2007; Wyder et al., 2005; Arnouts et al., 2005; Schiminovich et al., 2005).

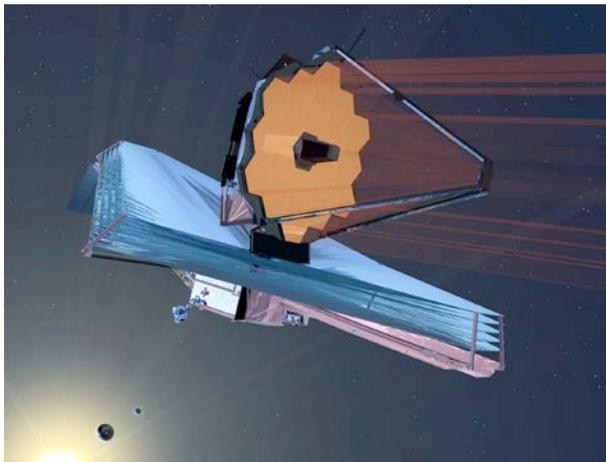
The UV-optical color-magnitude diagram (UVOCMD) is a powerful tool for separating and relating galaxy types, properties, and evolutionary histories,

largely because of the great leverage obtained with the UV (SFR)—optical/NIR (stellar mass) color. The UVOCMD can be measured accurately in very distant samples, and may be considered an HR diagram for galaxies in which stellar mass is the major predictor of galaxy properties. GALEX UVOCMDs first identified the tendency of AGN to occur preferentially in the “green valley.” (Wyder et al., 2007; Schiminovich et al., 2007; Martin et al., 2007)

GALEX has discovered a rare population of UV-luminous galaxies (UVLG), low-redshift starbursts with properties similar to high-redshift Lyman Break Galaxies (LBGs) (Heckman et al., 2005). GALEX deep surveys show that these UV-luminous galaxies (UVLGs) are the fastest-evolving component of the UV galaxy population. (Schiminovich et al., 2005) and are less dust-attenuated than other local starbursts, such as ULIRGs. This is consistent with an early stage of chemical evolution (Basu-Zych, et al., 2007; Hoopes et al., 2007). HST images of GALEX-discovered compact UVLGs reveal that they represent a complex merger of multiple, lower-mass, gas-rich subunits that echo the morphology and physical properties of high-*z* LBGs. Missions and Instruments in Development

### James Webb Space Telescope

The James Webb Space Telescope (JWST) is a large (6.5m), cold (50K) facility-class general-purpose observatory that will be launched into orbit around the Sun-Earth L2 point in 2013. It is the successor to the Hubble and Spitzer space telescopes. Its science goals



Artist's view of the James Webb Space Telescope. Credit: NASA/JWST

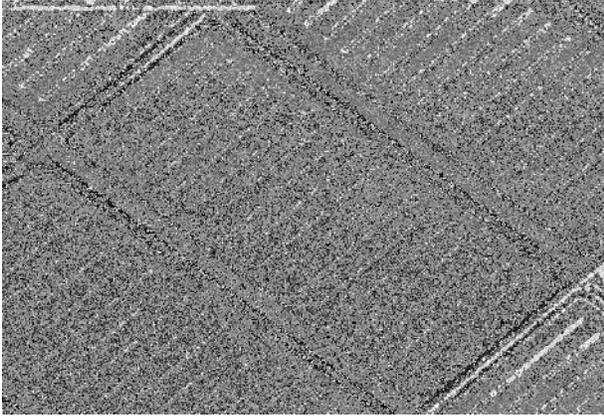
range from detecting the first galaxies to form in the early universe to observing objects in our solar system. Time on the telescope will be allocated to the community through annual peer-reviewed proposals, in a manner similar to Hubble. The prime contractor is Northrop Grumman Space Technologies; the Science and Operations Center is located at the Space Telescope Science Institute. For the prime mission, NASA is partnering with the European and Canadian Space Agencies.

**JWST is the successor to the Hubble and Spitzer space telescopes. Its science goals range from detecting the first galaxies to form in the early universe to observing objects in our solar system.**

The ASD provides scientific direction for JWST through seven project scientists. The Senior Project Scientist is John Mather and his deputy is Jonathan Gardner. The other members of the team: Matthew Greenhouse (Instrumentation), Bernard Rauscher (deputy); Mark Clampin (Observatory), Charles Bowers (deputy); and George Sonneborn (Operations). The ASD is currently seeking to hire an Associate Project Scientist for Integration and Test who will join the team to watch over the assembly, integration, test and commissioning of the Integrated Science Instrument Module (ISIM), the Optical Telescope Element (OTE) and the observatory.



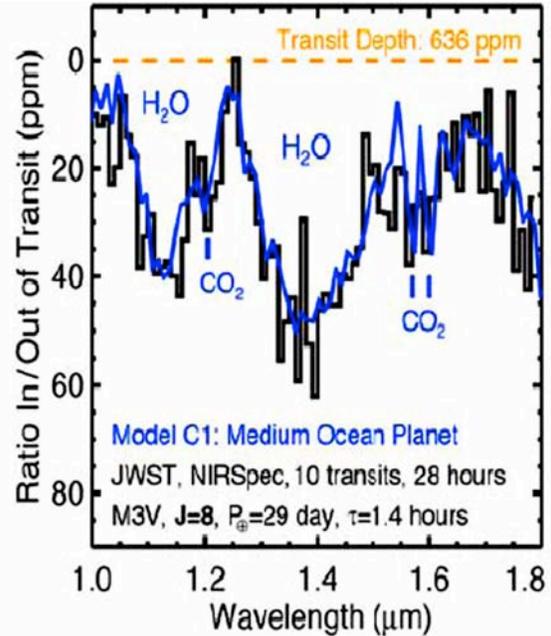
A primary mirror segment is prepared for cryogenic optical testing in the XRCF at MSFC. Credit: NASA/MSFC



A single JWST microshutter. The Microshutter Assembly consists of a mosaic of four subunits producing a final array of approximately 750 (spectral) by 350 (spatial) individually addressable shutters with  $200 \times 450$  milliarcsec openings and  $250 \times 500$  milliarcsec pitch. The minimum aperture size is 1 shutter (spectral) by 1 shutter (spatial) at all wavelengths. It represents the first time that a true multi-object spectrograph has flown in space. Credit: NASA/GSFC

Mather chairs the JWST Science Working Group (SWG), and the Project Scientists are thoroughly integrated with the management and engineering teams, participating in reviews, project meetings, serving on change-configuration boards, and participating in decisions. The JWST SWG recently published a thorough description of the JWST science goals and technical implementation as a special issue of the refereed journal, *Space Science Reviews* (Gardner et al., 2006). They have also produced a series of white papers extending the science case in certain areas, including astrobiology, exoplanet coronagraphy, exoplanet transits, first-light galaxies, and resolved stellar populations. An additional white paper on solar system observations is in preparation, and the white paper on exoplanet transits is being extended and prepared for refereed publication.

In 2008, JWST was confirmed for implementation, a transition that began with the Preliminary Design Review in April 2008. The Project is now in phase C/D, and the project is working towards the Critical Design Review (CDR) in late 2009. All four instruments have passed their CDRs and are scheduled to be delivered to Goddard for integration into the ISIM starting in early 2010. The 18 primary mirror segments,



Simulated JWST spectra of a transiting habitable Earth-sized ocean planet. Credit: NASA/JWST

three spares, and the secondary and tertiary mirrors have been constructed out of light-weight beryllium and are in various stages of grinding and polishing. An engineering-demonstration segment and the first flight segment went through cryogenic figure test at MSFC in January 2009. The mission has been managed within the same budget and scheduled launch date since 2005.



An engineering model of the Mid-Infrared Instrument went through thermal vacuum testing in 2008

The ASD is directly responsible for two hardware items, both within the Near-Infrared Spectrograph (NIRSpec), an instrument that is part of the ESA contribution to the mission. The Microshutter Assembly (MSA) is led by PI Harvey Moseley with contributions from Robert Silverberg and a number of contractor scientists. The MSA will enable simultaneous spectra of more than 100 objects—the first time that a true multi-object spectrograph has flown in space. The MSA is scheduled for delivery to ESA in March 2009. The detectors in the NIRSpec are also being built at Goddard, under the leadership of Bernard Rauscher, and will also be delivered in 2009. Both Rauscher and Moseley are members of the NIRSpec Science Teams and will participate in their Guaranteed Time Observations.

### Joint Dark Energy Mission (JDEM)

The 1998 discovery that the expansion of space is accelerating was described by the journal *Science* as the breakthrough of the year and one of the most important scientific problems of our time. The implication that three-quarters of the energy in the universe is due to an unknown entity now called “dark energy” may revolutionize our understanding of cosmology and physics when this phenomenon is one day fully characterized. Observations with ground-based and orbital assets, including HST, Chandra, and WMAP, confirm the acceleration. However, to advance understanding in this critical area of new physics, we need a new space-based experiment to extend ground-based measurements of dark energy to the early universe with high precision.

Between 2003 and 2006, NASA solicited concepts for such a dark energy mission to inform joint planning between the agency and its partner, the U.S. Department of Energy (DOE). The latter set of mission-concept studies completed in September 2008. ASD scientists were heavily involved in all three funded mission concepts. Benford, Carpenter, and Sonneborn were on the DESTINY (supernovae and weak lensing) science team; Moseley, Hinshaw, Oegerle, and Bowers were on the ADEPT (baryon acoustic oscillations and supernovae) team; and Woodgate, Rauscher, Kimball, and Greenhouse were members of the SNAP (supernovae and weak lensing) team.

At the conclusion of these community-led studies, NASA and DOE announced plans for developing JDEM as an agency strategic mission with a NASA Announcement of Opportunity (AO) solicitation for JDEM flight-mission science investigations. The agencies also published their memo of understanding for joint development of the mission, including space and ground segments and science instrumentation. NASA then established the JDEM Project Office at the Goddard Space Flight Center to implement the NASA portion of the agreement.

**To advance understanding of dark energy, we need a new space-based experiment to extend ground-based measurements to the early universe with high precision.**

In October 2008, NASA and DOE selected a Science Coordination Group (SCG) via an open “Dear Colleague” letter to distill a reference mission from the above concept studies consistent with programmatic constraints for mission implementation and a boundary condition enabling three prime experimental methods for the investigation of dark energy. The chair of the SCG is the NASA JDEM Project Scientist Dr. Neil Gehrels (ASD) and members of the SCG include ASD scientists Benford and Moseley.

The primary initial task of the GSFC JDEM Project has been to work, with the guidance of the SCG, to create a set of mission requirements, and a reference mission that will meet them, to support the release of the science investigation AO. The JDEM project has been examining the design space required to accommodate all of the principal measurement techniques funded for study; which include Baryonic Acoustic Oscillations, Type 1a supernovae, and weak lensing. The current design incorporates solutions required to robustly carry out all three types of measurements.

The concept for this reference mission is the point of departure for the phase A mission study now in progress (Oct. 2008 through Sept. 2009). The JDEM Phase A study will focus exclusively on enabling the specific science investigations selected by the AO. We expect that the investigators selected by this AO will



The Astro-H spacecraft. Credit: JAXA

form a standing flight Science Working Group to advise the JDEM Project throughout all future phases of mission development and operations.

The GSFC JDEM Project utilizes the skills of a broad cross-section of GSFC personnel, including project managers, project scientists, resources/financial specialists, and engineers. It is a collaborative effort across multiple GSFC directorates, including Science, Engineering, and Flight Projects). The GSFC Project looks forward to working with its counterparts within the DOE, and if current negotiations are fruitful, within the European Space Agency (ESA) as well.

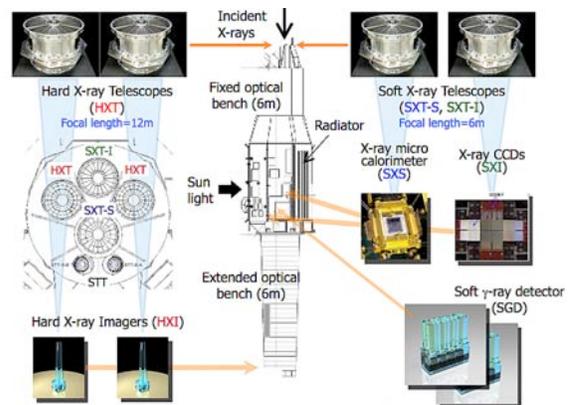
### Astro-H

The X-Ray Astrophysics Laboratory is collaborating with ISAS/JAXA to implement an X-ray calorimeter spectrometer for the Astro-H mission. In response to the 2007 NASA Announcement of Opportunity soliciting investigations for Small Explorer (SMEX) missions and Missions of Opportunity (MO), a group headed by Richard Kelley of the X-Ray Astrophysics Laboratory was selected to provide key components of a high-resolution X-ray calorimeter spectrometer that will constitute one of the observatory's primary science instruments.

**The X-Ray Astrophysics Laboratory at Goddard was selected to provide key components of a high-resolution X-ray calorimeter spectrometer that will constitute one of the observatory's primary science instruments.**

The Soft X-ray Spectrometer (SXS) will consist of a 64-pixel X-ray calorimeter array with better than 7 eV resolution (and a goal of 4 eV) to provide high-resolution X-ray spectroscopy over the 0.3–12 keV band with moderate imaging capability. The Goddard team is to provide the detector system, adiabatic demagnetization refrigerator (50 mK operational temperature), electronics, blocking filters and X-ray mirror, while ISAS/JAXA is responsible for the dewar system and the rest of the science instruments, the spacecraft, launcher, and mission operations. The dewar will be a hybrid cryogen/mechanical cooler system for redundancy, and the X-ray mirror will build on the Goddard legacy of providing lightweight, high-throughput mirrors.

Astro-H is a facility-class mission to be launched on a JAXA H-IIA into low Earth orbit in mid-2013. The Astro-H mission objectives: trace the growth history of the largest structures in the universe; provide insights into the behavior of material in extreme gravitational fields; determine the spin of black holes and the equation of state of neutron stars; trace shock-acceleration structures in clusters of galaxies and SNRs; and investigate the detailed physics of jets. Achieving



An overview of planned instrumentation for Astro-H. Credit: NASA/JAXA

these objectives requires the SXS and three additional scientific instruments to provide a very broad, simultaneous energy bandpass.

The Hard X-ray Imager (HXI) will perform sensitive imaging spectroscopy in the 5–80 keV band; the non-imaging Soft Gamma-ray Detector (SGD) extends the Astro-H energy band to 300 keV, and the Soft X-ray Imager (SXI) expands the field of view with a new-generation CCD camera.

The proposed SXS science investigation comprises building and delivering the SXS instrumentation and carrying out a six-month observing program in collaboration with ISAS/JAXA. The baseline mission includes two years of funding for the SXS science team and support for processing and archiving the SXS data for a total of three years. A Science Enhancement Option (SEO) was also proposed to provide the US community with access to Astro-H beyond the baseline program. Under the SEO, U.S. scientists will be able to propose for Astro-H observing time and obtain grant support. Working collaboratively with JAXA, a U.S. Guest Observer Facility will process, distribute, and archive data from all four Astro-H instruments, and provide observers with analysis tools and support. NASA will address the SEO portion of the proposal at a later date.

## SOFIA/SAFIRE

The Submillimeter and Far-InfraRed Experiment (SAFIRE) on the SOFIA airborne observatory is a spectrometer operating at wavelengths between  $\sim 100 \mu\text{m}$  and  $\sim 450 \mu\text{m}$  (Harvey Moseley, PI; Dominic Benford, Deputy PI). SAFIRE's key science goal is

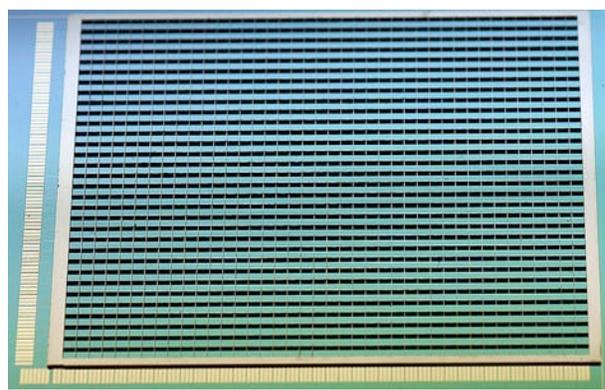
to investigate line emission in galaxies at wavelengths not visible from the ground and to map the variation in this line emission in nearby galaxies. SAFIRE's top priority observations will be to measure emission lines in the Galactic center, to map emission lines in nearby galaxies, and to understand the physics of the cores of ultraluminous galaxies from the local region to the high-redshift universe through far-infrared fine-structure line emission. SOFIA will fly at an altitude where the atmosphere is mostly transparent, permitting SAFIRE to achieve a high point-source sensitivity at most wavelengths. When SAFIRE achieves first light in 2013, it will add substantial capability to the first-light instrument complement of SOFIA.

**When SAFIRE achieves first light in 2013, it will add substantial capability to the first-light instrument complement of the SOFIA airborne observatory.**

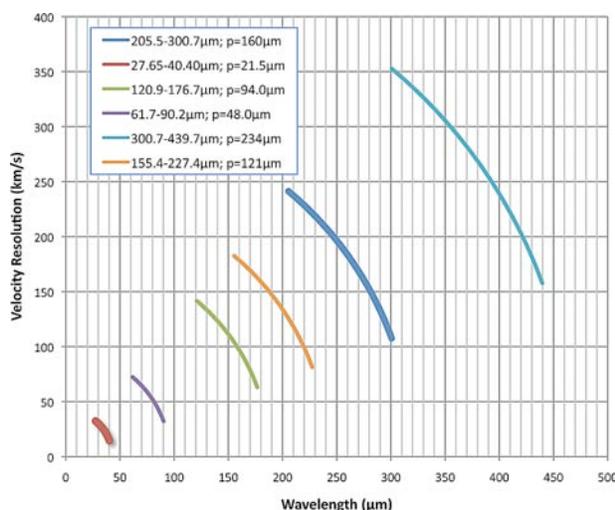
SAFIRE is a cryogenic instrument in a space-constrained environment, so developing and implementing a suitable optical design is challenging. During the past year, optical design trade studies have transformed the original proposed design—an imaging Fabry-Pérot interferometer—into a dual long-slit tunable grating spectrometer. The new design has the advantage of higher efficiency, faster observations for most sources, and increased flexibility in wavelengths of operation. Each of the gratings (and corresponding bandpass filters and slits) would be interchangeable to permit a wide variety of wavelength ranges—perhaps to wavelengths as short as  $28 \mu\text{m}$  (where JWST's MIRI cuts off). The most common optical configuration would



The SOFIA observatory.



A mechanical prototype detector array.



The grating set available for SAFIRE.

feature one grating channel operating between 120  $\mu\text{m}$  and 180  $\mu\text{m}$  with a velocity resolution of around 100 km/s and a slit size of  $8'' \times 320''$ , and another channel at 205  $\mu\text{m}$  to 300  $\mu\text{m}$  at 170 km/s with a slit size of  $12'' \times 320''$ . This configuration permits studies of the ionized carbon line at 158  $\mu\text{m}$  simultaneously with the ionized nitrogen line at 205  $\mu\text{m}$ .

The enabling technology for SAFIRE is its large-format superconducting bolometer arrays, under development by scientists in ASD (Harvey Moseley and team). In order to span the wide wavelength range envisioned—over two octaves—SAFIRE has been designed with a pair of  $32 \times 40$  (1,280 pixel) arrays. This provides for both a long slit width and a large instantaneous velocity resolution of  $\sim 3000$  km/s that enables rapid mapping of nearby galaxies and searches for redshifts or more distant sources.

### Gravity and Extreme Magnetism SMEX (GEMS)

The information contained in the polarization of X-ray fluxes has long been viewed as the unexplored handle on the geometrical and magnetic structures of X-ray-emitting regions. Sensitivity to the effects of strong gravity around black holes and the virtual pair creation of strong magnetic fields in neutron stars give polarization a special place as a probe of fundamental physics.

In December 2008, a Phase A Concept Study Report was submitted to the SMEX program for the Gravity and Extreme Magnetism SMEX (GEMS). Jean Swank is the Principal Investigator. The GEMS team is very excited that their design could carry the most efficient possible 2–10 keV polarization experiment for a SMEX envelope, and that it would be able to make ground-breaking measurements of many classes of X-ray source. The team is preparing for the site visit of the Review committee, to be held in April 2009.

GEMS carries three telescopes, with each of the mirrors being a copy of the 4.5m focal length Suzaku mirror. The detectors behind the mirrors are Time Projection Chambers in which micropattern gas detectors record the tracks of photoelectrons as they lose energy. The mirrors and the polarimeters for GEMS are optimized for 2–10 keV. The spacecraft will rotate at 0.1 rpm to allow systematic affects to be detected and corrected. The rotation allows a student experiment from co-investigators at University of Iowa to measure the polarization at 0.5 keV by scattering these X-rays out of the beam from one of the mirrors into a small proportional counter.

**The GEMS team believes this design could carry the most efficient possible 2–10 keV polarization experiment for a SMEX envelope, and that it would be able to make ground-breaking measurements of many classes of X-ray source.**

The 1972 rocket flight detection of polarization of the Crab Nebula X-ray flux was followed by spacecraft efforts to detect polarization in bright sources using Bragg scattering instruments. These had good sensitivity to the polarization of an X-ray but very low sensitivities as instruments. The sensitivity of the photoelectric effect to the polarization of the X-ray raised the possibility of more efficient instruments. To use this effect it is necessary to track the ejected electrons whose distribution is peaked around the direction of the electric vector. In several early laboratory efforts to do this, the tracks were too short. It was achieved in a potentially practical way by Bellazini at INIF, as reported in the paper by Costa et al. (2001).

Work on micropattern gas detectors in ASD led to a 2003 SMEX proposal for the Advanced X-Ray Polarimeter (AXP), in collaboration with Palo Alto Research Center and the Italian INFN and IASF-CNR. While AXP was not selected, funding for detector development permitted continued laboratory work. The GEMS polarimeters are several times more efficient than the AXP polarimeters. Detector work in the X-Ray Astrophysics Lab led to adopting the detectors used in particle-physics experiments to our application.

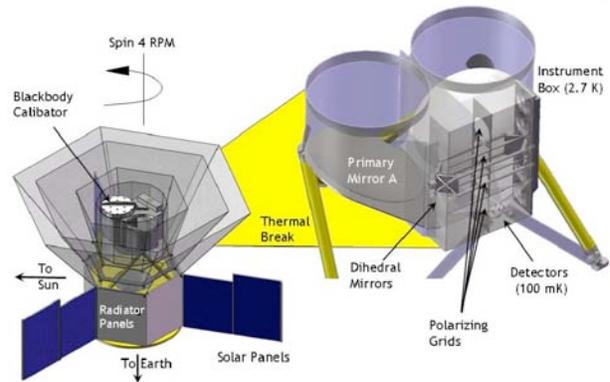
The more efficient polarimeters will make possible measurement of polarization to an accuracy of about 1% for representatives of stellar black holes, supermassive black holes, neutron star pulsars (including magnetars), and supernova remnants. The baseline science program can be carried out in nine months with 35 targets. In the balance of a two-year mission, a General Observer (GO) program could measure the polarizations of as many more targets. The Science Operations would be set up to support GOs as well as the baseline mission.

GEMS combines the X-Ray Astrophysics Laboratory's interests in instruments and in the physics of astrophysical sources. Polarization data, as well as timing and spectroscopy data, will provide a robust guide to resolving alternative interpretations of X-ray emission in various cosmic sources.

### *Mission Concepts*

#### **Absolute Spectrum Polarimeter (ASP)**

The Absolute Spectrum Polarimeter (ASP) is an Explorer-class mission concept to measure the polarization pattern and frequency spectrum of the cosmic microwave background. ASP will measure the linear polarization produced by gravity waves excited during an inflationary epoch shortly after the Big Bang. Such a signal is expected to exist; its detection would have profound consequences for both cosmology and particle physics. Not only would it establish inflation as a physical reality, but it would provide a model-independent determination of the relevant energy scale ( $\sim 10^{15}$  GeV) some twelve orders of magnitude beyond those accessible to particle accelerators.



Schematic view of the Absolute Spectrum Polarimeter spacecraft. Credit: NASA/GSFC

ASP uses a cryogenic Michelson interferometer to measure the differential spectrum between two independent inputs in two orthogonal linear polarizations. ASP will measure the frequency spectrum of the Stokes I, Q, and U parameters from 1 cm through 60  $\mu\text{m}$  wavelength. Its high sensitivity and broad spectral coverage enable a range of science goals. The polarization on large angular scales encodes the ionization fraction as a function of redshift, providing critical inputs for models of reionization and structure formation.

**ASP will measure the spectra of the temperature and polarization anisotropy to confirm their cosmological origin and will measure both the far-infrared background and its power spectrum to test models of structure formation.**

Measurements of the CMB blackbody spectrum provide an independent determination of reionization through the Sunyaev-Zeldovich spectral distortion and will search for evidence of dark matter decay or annihilation in the very early universe ( $10^7 < z < 10^3$ ). ASP will measure the spectra of the temperature and polarization anisotropy to confirm their cosmological origin, and will measure both the far-infrared background and its power spectrum to test models of structure formation. Its measurements of the diffuse interstellar medium include full-sky maps of the major C+, N+, OI, and CO lines as well as thermal dust, free-free, and synchrotron emission.

## International X-ray Observatory (IXO)

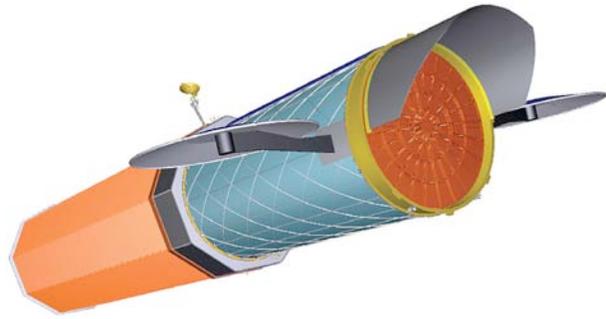
IXO is a new X-ray telescope with joint participation from NASA, the European Space Agency (ESA), and Japan's Aerospace Exploration Agency (JAXA). This project supersedes both NASA's Constellation-X and ESA's XEUS mission concepts. IXO is a facility-class mission for launch circa 2020 that will address the leading astrophysical questions in the "hot universe" through its breakthrough capabilities in X-ray spectroscopy, imaging, timing, and polarimetry.

IXO will measure the spin of black holes, a fundamental property that, for supermassive black holes, reveals whether black holes grow mainly by accretion or by mergers. IXO will reveal the physics of accretion near the last stable orbit, measuring general-relativistic effects in the strong field limit. For neutron stars, IXO will determine the mass-radius relationship, thereby constraining the equation of state and QCD models of matter at these densities. In galaxy clusters, IXO will measure the velocity structure, mass, and metallicity distribution of the dominant baryon component, the hot intracluster gas. Not only will this provide a deep understanding of evolution of large-scale structure, but samples of clusters at various redshifts provide important and independent constraints on the cosmological model and dark energy.

**IXO is a facility-class mission for launch circa 2020 that will address the leading astrophysical questions in the "hot universe"**

Extending away from clusters and groups is the cosmic web, where half of the baryons in the local universe are expected to reside but have not been detected. IXO will detect these missing baryons and it can test predictions for the formation and topology of the cosmic web. Furthermore, IXO will yield insight into feedback mechanisms in the universe on many scales: through studies of supernova remnants, outflows in starburst galaxies, and AGNs across cosmic time.

Much of this science requires a panchromatic approach. IXO covers the 0.1–40 keV energy range, complementing the capabilities of the next-generation observatories such as ALMA, LSST, JWST and 30m



Mechanical engineering model of the IXO spacecraft. The front of the spacecraft has a sunshade for the opening of the X-ray mirror. Shown here is the slumped-glass mirror concept. The orange aft end of the spacecraft features an extendible optical bench; the instrument focal plane is at the end. Credit: NASA/IXO

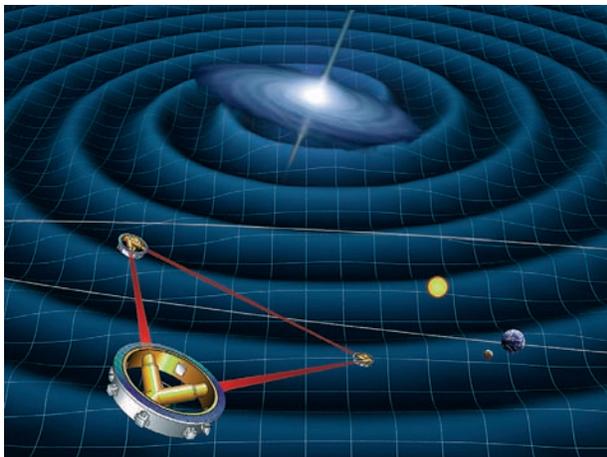
ground-based telescopes. IXO builds on three decades of successful X-ray telescope development, including the currently operating Chandra X-ray Observatory (NASA) and XMM-Newton mission (ESA). The spacecraft configuration for IXO features a single, large X-ray mirror assembly and an extendible optical bench, with a focal length of  $\sim 20\text{m}$ , and a suite of focal plane instruments. Areas of technology development include X-ray optics, detector and cooling systems. The NASA portion of this project is led by GSFC (the Project Scientist is Nicholas White, Deputy Project Scientist is Ann Hornschemeier, and the Observatory Project Scientist is Rob Petre).

## Laser Interferometer Space Antenna (LISA)

The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA project to design, build and operate a space-based gravitational wave detector. Space-time strains induced by gravitational waves are detected by measuring changes in the separation of fiducial masses with laser interferometry. Three spacecraft form an equilateral triangle with 5-million-kilometer-long sides defined by six proof masses, located in pairs at the vertices. Changes in the separations are monitored interferometrically to achieve a usable sensitivity in the frequency band between  $1 \times 10^{-4}$  and 0.1 Hz

The science objectives of the missions are:

- Understand the formation and growth of massive black holes and their host galaxies;



LISA will use three spacecraft to form an equilateral triangle with 5-million-kilometer-long sides defined by six proof masses, located in pairs at each vertex. Credit: NASA/ESA

- Make precision tests of general relativity and dynamical strong-field gravity;
- Survey ultra-compact binaries and study the morphology the Galaxy;
- Explore stellar populations and dynamics in galactic nuclei;
- Probe new physics and cosmology.

Although the gravitational wave spectrum has not yet been explored, LISA is expected to make precision measurements of the following sources:

- Merging massive black holes resulting from galaxy and proto-galaxy mergers:  $10^2$ – $10^7$  solar masses,  $z < 20$ , tens to 100 per year;
- Stellar mass black hole inspirals:  $\sim 10/10^6$  solar masses,  $z < 1$ , tens to 100 per year;
- Galactic and extra-galactic ultra-compact binaries: tens of thousands, confusion foreground;
- Cosmological backgrounds, bursts and unforeseen sources.

The LISA Project Office is at GSFC. The Gravitational Astrophysics Laboratory provides the Project Scientist (Tuck Stebbins), three Deputy Project Scientists (Steve

Merkowitz, Jeff Livas, Jordan Camp), and about 10 other scientists who support project formulation, mission system engineering, technology development, risk reduction activities, astrophysical source studies, numerical relativity calculations of source waveforms, LISA data analysis research, and LISA Pathfinder data analysis.

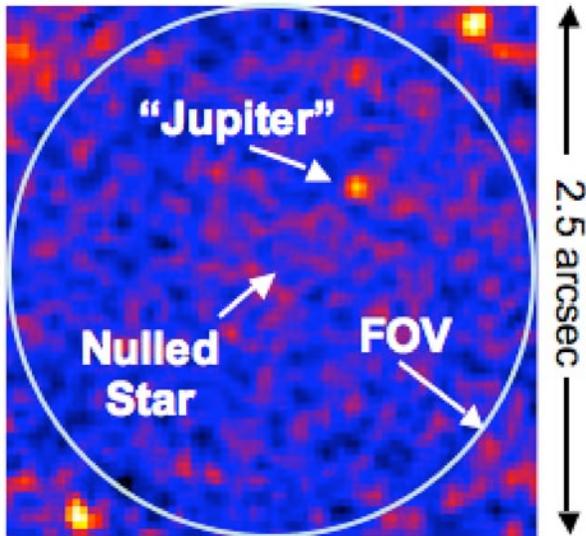
Goddard scientists support all aspects of project formulation, notably requirements development and flowdown, system analysis, system modeling, design of all mission elements, trade studies and document preparation. Goddard technology development work focuses on lasers, laser frequency stabilization (including pre-stabilization and arm-locking), and I&T technologies. Goddard risk-reduction activities include telescope construction, prototyping a critical mechanism, and control system modeling. The numerical relativity group in the Gravitational Astrophysics Lab has led the way in producing merger phase waveforms for inspiraling black holes, a crucial ingredient in LISA data analysis.

**The numerical relativity group in the Gravitational Astrophysics Lab has led the way in producing merger phase waveforms for inspiraling black holes, a crucial ingredient in LISA data analysis.**

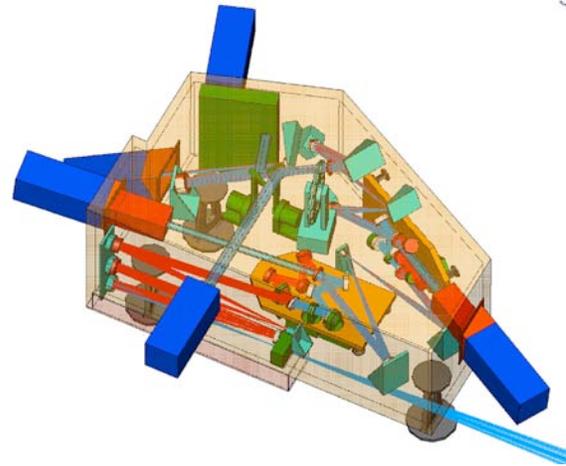
### Extrasolar Planetary Imaging Coronagraph (EPIC)

Direct imaging/characterization of exosolar planets is predicated on the ability to unambiguously detect planets in the presence of diffracted/scattered light from the parent star, its exozodiacal light and other objects in the field of view. Astrometric missions can detect Earth-mass planets and determine orbital parameters yet cannot determine the zodiacal light—crucial for a future exosolar terrestrial imaging mission.

EPIC is an alternative approach which images and characterizes jovian planets and exozodi disks around single, binary and ternary stars. It would provide the first direct measurements of a range of fundamental physical characteristics of exosolar giant planets—a



This image shows a simulated EPIC planetary detection. Credit: NASA/EPIC

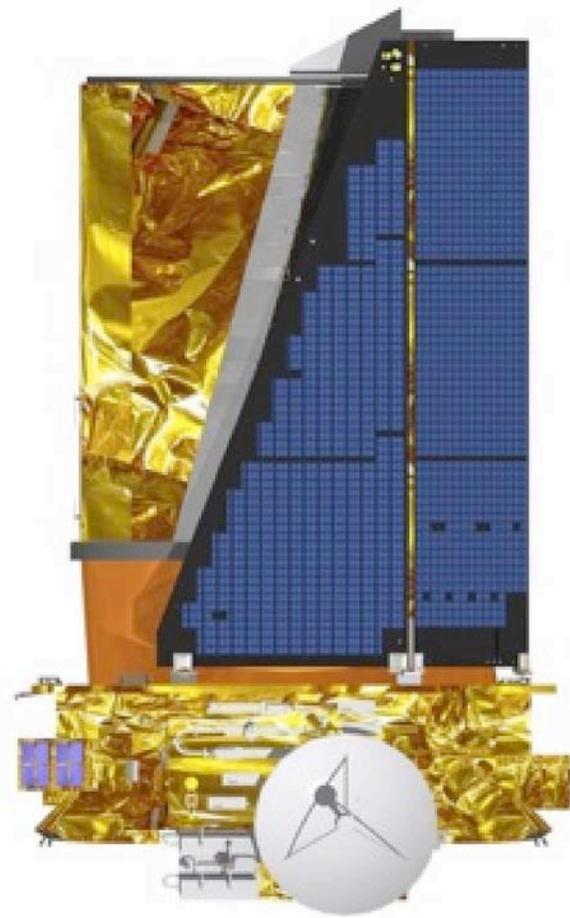


A schematic view of the EPIC Visible Nulling Coronagraph. Credit: NASA/EPIC

step toward the long-term goal of imaging exosolar terrestrial planets (Mark Clampin, PI; Gary Melnick/CfA, Deputy PI; Rick Lyon, Project Scientist).

Science goals are achieved by a 1.65-meter telescope coupled to a visible nulling coronagraph (VNC) delivering broadband starlight suppression ( $10^9$  @ 125 mas) and permitting direct observation and broadband (0.4 – 1.0  $\mu\text{m}$ ) spectral characterization. EPIC is aligned with the strategic objectives of NASA per “The New Age of Exploration” and fulfills the goal of “Vision for Space Exploration,” which calls for planet searches. EPIC meets the recommendations of the Exoplanetary Task Force (ExoPTF) to characterize exosolar disks and is a funded Astrophysics Strategic Mission Concept study (ASMC). The results of the study will be presented to the Decadal review.

**EPIC would provide the first direct measurements of a range of fundamental physical characteristics of exosolar giant planets—a step toward the long-term goal of imaging exosolar terrestrial planets.**



Artist's concept of the EPIC spacecraft. Credit: NASA/EPIC

EPIC has been proposed as a NASA/Discovery mission. The EPIC team, including industrial partners Lockheed-Martin (telescope & VNC), Ball Aerospace (S/C bus) and the GSFC Instrument Design Center, have conceived a mature design using heritage technology (Kepler, Deep Impact) for a Probe class mission (<

\$800M). The design includes extensive mission- and systems-level engineering down to the sub-system/component level, leading to a well-balanced error budget with a low-risk design and realizable mission.

GSFC IR&D funding is enabling demonstration of the critical VNC technology via the VNC testbed and Null Control Breadboard (NCB). This vacuum testbed will demonstrate the requisite TRL-6 requirement of  $10^9$  contrast in 15% passband for greater than 1,000 secs.

### The Fourier-Kelvin Stellar Interferometer (FKSI)

The long-term focus of planet-finding efforts at NASA has been directed toward the search for extrasolar terrestrial planets, like those in our own solar system, within the habitable zone around stars similar to our own Sun, e.g., F, G, and K main sequence stars. Our present theoretical understanding is that all planets form out of material in primordial disks from which the stars themselves accreted material. Thus, the formation of planets is intimately linked to the evolution of circumstellar disks, which for mature stars like our own Sun, have optically thin “debris disks” in their habitable zones.

Recent studies of the requirements for planet-finding-and-characterization missions such as the Terrestrial Planet Finder (TPF) have shown that the amount of exozodiacal emission from warm and hot dust in the

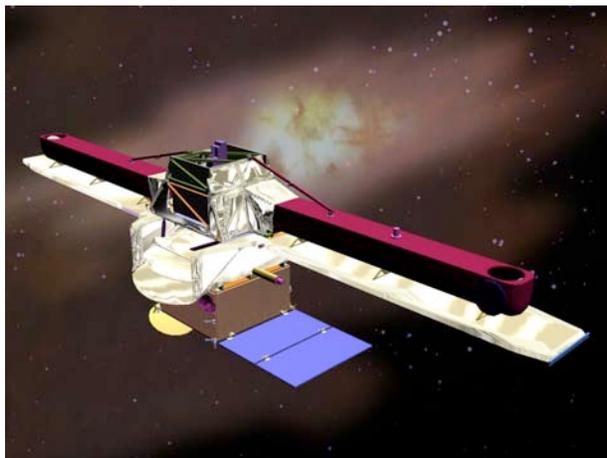
habitable zone is a crucial parameter. Observations of planets in stellar systems with more than about 10 times the zodiacal light as our solar system will be extremely difficult, as exozodiacal dust emission (and/or scattering) interferes with the observer’s ability to detect the faint emission from an earthlike planet.

**FKSI's main goals are the measurement and characterization of the exozodiacal emission around nearby stars, debris disks, spectroscopic characterization of the atmospheres of known exoplanets, and the search for and characterization of super Earths around nearby stars.**

Thus it is crucial to observe all of the likely targets for TPF to determine the amount of exozodiacal emission around nearby stars with sufficient accuracy for the flagship missions. In particular we must answer the question: What is the star-to-star statistical distribution of exozodiacal material in the habitable zone around nearby stars? The need for this measurement is documented in the report from the ExoPlanetary Task Force (Lunine et al., 2008). This measurement can be made with a small infrared interferometer having apertures  $\sim 0.5$ – $1$  m in diameter and which is passively cooled to about 60 K.

One such implementation is the Fourier-Kelvin Stellar Interferometer (FKSI) mission, which is an infrared space interferometer comprised of two 0.5-m-aperture telescopes on a 12.5-m baseline on a boom, operating in the spectral range 3 to 8 (or 10) microns, and passively cooled to about 60 K. Bill Danchi is the Principal Investigator for FKSI. The main goals for this mission are the measurement and characterization of the exozodiacal emission around nearby stars, debris disks, spectroscopic characterization of the atmospheres of known exoplanets, and the search for and characterization of super Earths around nearby stars.

The FKSI mission has been reviewed in the context of the Exoplanet Community Forum 2008 and has been included in the notional timeline developed for the area of “Direct Infrared Imaging of Exoplanets” as a candidate for a mid-sized or Probe-class strategic mis-



Artist's conception of the FKSI mission concept. This prototype planet-finding mission has been extensively studied. Credit: NASA/GSFC

*On the Web*

Exoplanet Community Forum Report  
[exep.jpl.nasa.gov/documents/  
 Forum2008\\_268\\_small.pdf](http://exep.jpl.nasa.gov/documents/Forum2008_268_small.pdf)

sion (see the Exoplanet Community Forum Report, Chapter 4). Most of the technical risks have been retired through technology investments for JWST, SIM, and TPF-I/Darwin, and most technologies are at a Technical Readiness Level (TRL) sufficient for advancement to Phase A. This mission could receive a Phase A start in the next 2–5 years with only modest technology investments.

### Terrestrial Planet Finder/Galaxy Evolution Surveyor

A terrestrial-planet finding telescope with a large, external occulter (TPF-O) has been under development at Goddard since December 2005. It is the outgrowth of a Discovery proposal led by W. Cash (Univ. of Colorado) with Goddard as lead NASA center. The proposal was to provide JWST with an occulter, which would enable it to discover Earth-size planets that might be habitable. The experience gained in that



Goddard scientists and engineers are considering an optimal planet-finding occulter: a 4m UV-optical telescope paired with a 50m occulter flying 70,000 km in front of the telescope along the line of sight to the target. Credit: NASA/GSFC

proposal effort led Goddard scientists and engineers to consider an optimal TPF-O: a 4m UV-optical telescope equipped with cameras and integral-field spectrographs, paired with a 50m occulter flying 70,000 km in front of the telescope along the line of sight to the target star.

Today, Goddard scientists are helping to refine that concept by participating in two of NASA's astrophysics mission concept studies. Roberge is a coinvestigator on the New Worlds Observer (W. Cash, PI), and Heap, Kuchner, Lindler, and Lyon are co-investigators on the ExoPlanet Characterizer, now incorporated into THEIA (D. Spergel, PI).

**An early proposal to outfit JWST with an occulter to enable discovery of Earth-size planets has led Goddard scientists and engineers to consider an optimal planet-finding occulter mission.**

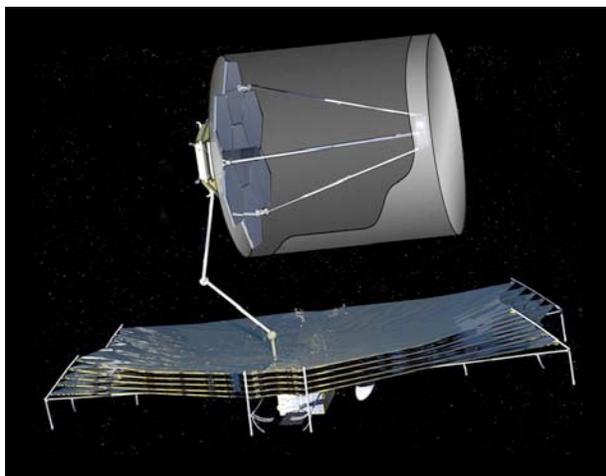
They are also carrying out independent research supported entirely by Goddard:

- Design a testbed for TPF-O to explore the starlight-suppression properties of the occulter and to demonstrate closed-loop control of the occulter (Lyon & Heap).
- Develop the science case for TPF-O with special emphasis on the 100-fold increased sensitivity to photosynthesizing organisms enabled by a UV ozone camera (Heap & Lindler). The science case is buttressed by design reference missions, which allow the scientific gains to be quantified.
- Develop “revolutionary” astrophysics instrumentation for TPF-O, as directed by the 2000 Astrophysics Decadal survey panel. Heap and Lyon are collaborating with Massimo Robberto (STScI) to develop a concept for a wide-field imager/multi-object spectrograph primarily for studies of galaxy evolution but applicable to studies of dark energy and dark matter as well. Like the instrument proposed for SPACE (now incorporated into EUCLID), the spectrograph would use commercial digital micromirror devices (DMDs) to mask off

selected objects for spectroscopy. However, the TPF-O version will have miniaturized fore and aft optics to the DMDs so as to make room for an array of multiobject spectrographs sampling a wide field of view.

### Advanced Technology Large Aperture Space Telescope (ATLAST)

ATLAST is a concept study consisting of three point designs for an 8- to 16-meter UV/optical/NIR observatory designed for operation in a halo orbit at the Sun-Earth second Lagrange point (SEL2). ATLAST would have an angular resolution 5–10 times better than the James Webb Space Telescope (JWST) and a sensitivity limit 40–300 times better than the Hubble Space Telescope (HST). This concept was selected for study by NASA as one of the Astrophysics Strategic Mission Concept studies in preparation for the National Academy’s Astro2010 Decadal Survey. Marc Postman (STScI) is the Principal Investigator and GSFC is the managing NASA Center. Team members include JPL, NGST, Ball Aerospace and scientists from the community. ASD scientists involved in the study include Mark Clampin, Ted Gull, Rick Lyon, Bill Oegerle, Jennifer Wiseman, and Bruce Woodgate, as well as a number of people from the GSFC Engineering Directorate.



One of three designs under study for ATLAST is a 16m segmented-aperture telescope. This builds on the JWST heritage for its segmented design and folded packaging. Credit: NASA/STScI/J.

The ATLAS Telescope is envisioned as a flagship mission of the 2025–2035 period designed to address one of the most compelling questions of our time: Is there life elsewhere in our Galaxy? It will have the capabilities required to explore the nearest ~1,000 stars capable of harboring life for Earth-size planets and characterize their spectra. ATLAST will also be a next generation UV/Optical Great Observatory—in the model established by HST—that is capable of achieving breakthroughs in a broad range of astrophysics and adaptable to addressing scientific investigations yet to be conceived. Indeed, such a telescope would revolutionize the study of galaxy evolution, enabling, for the first time, measurements of the kinematics of both the gaseous and stellar components of the smallest dwarf galaxies. It would yield such precise constraints on hierarchical-structure formation models that a new era of “precision galaxy evolution” would ensue. The superb spatial resolution would also allow unprecedented studies of resolved stellar populations in nearby galaxies.

**The ATLAS Telescope is envisioned as a flagship mission of the 2025–2035 period designed to address one of the most compelling questions of our time: Is there life elsewhere in our Galaxy?**

Two of the point designs (for an 8m monolithic mirror telescope and a 16m segmented, deployable-aperture telescope) are enabled by NASA’s plans for a large Cargo Launch Vehicle (the Ares V), which will have a fairing size of 9–10 meters in diameter and the lift capacity to take 100 metric tons to SEL2. The 8-meter monolith telescope would fit into the Ares V fairing with the secondary fully deployed in an upright position. This eliminates a lot of risk in deployment in orbit. The 16m segmented-aperture telescope builds on the JWST heritage in terms of its segmented design and folded packaging.

A third point design, being studied primarily at GSFC, is for a 9.2m segmented telescope that would fit into the fairing of an Evolved Expendable Launch Vehicle (EELV), such as the Delta IV heavy. All three point designs are identifying the technology investments

needed to enable these telescopes, such as lightweight mirrors with accurate figures, active wavefront sensing and control, and large-format detector technologies, to name just a few. The ATLAST study report will be delivered to NASA in April 2009 and to the Decadal Survey committee for consideration.

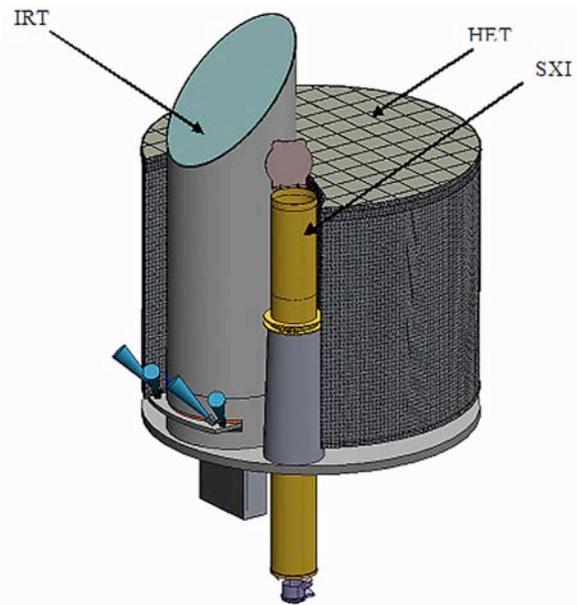
### Energetic X-ray Imaging Survey Telescope (EXIST)

EXIST is a concept for an all-sky hard-X-ray imaging and gamma-ray burst mission (Grindlay/CfA, PI). ASD team members include Barthelmy, Gehrels, Tueller, Band, and Skinner.

**EXIST would detect extremely faint high-energy X-ray sources in the 5–600 keV range, which is poorly explored but particularly important for the discovery and study of black holes.**

EXIST is based on proven technology and would image and temporally resolve the entire sky in every two 95-minute orbits. It would detect extremely faint high-energy X-ray sources in the 5–600 keV range, which is poorly explored but particularly important for the discovery and study of black holes. EXIST's primary science objectives are to:

- Study the earliest stars, reionization and development of structure in the universe with prompt hard X-ray and prompt followup NIR measurements of GRBs at  $z > 7$
- Constrain the accretion luminosity of the universe by measurements of high-luminosity obscured AGN at  $z \sim 0-2.5$ , low-luminosity AGN at  $z < 0.5$  and dormant AGN (from tidal disruption events) at  $z < 0.1$
- Provide the most sensitive wide-field measures of the transient universe with X-ray/OIR studies of blazars, black hole transients and high-energy variables (including stellar flares) with full-sky coverage every 3 hours, in synergy with GLAST and PanSTARRS, as well as LSST, JWST and other planned facilities.



The EXIST mission Instrument Module (spacecraft not shown). The three instruments are the High Energy telescope (HET), the Infrared Telescope (IRT) and the Soft X-ray Imager telescope (SXI). Credit: NASA/GSFC

The EXIST mission has evolved into the following configuration of three instruments: the High Energy Telescope (HET), an Infrared Telescope (IRT), and a Soft-X-ray Imaging telescope (SXI). In preparation for reports to the Astro2010 Decadal Survey, EXIST has conducted studies in the Goddard Instrument Design Lab (IDL) and the Mission Design Lab (MDL). The HET is 4.5m<sup>2</sup> of 5mm-thick CZT under a coded-aperture mask; the detectors are shown in the suborbital section under Proto-EXIST. The FOV is 90 × 70 deg at the 10%-coded region.

The mask is composed of two scales: a 3-mm-thick, 15-mm-cell-size mask pattern and a 0.3-mm-thick, 1.25-mm-cell-size pattern. This allows for quick localizations of gamma-ray bursts (GRB) within 10 sec using the course scale. The spacecraft then slews to point the IRT and SXI narrow-field telescopes within 120 sec. The IRT makes rapid imaging and spectral measurements to determine the redshift of the burst with ~600 sec. The SXI makes localizations, lightcurves, and spectra in the 0.2-8 keV band. In addition to rapid localization of GRBs, EXIST will also conduct a full-sky hard-x-ray survey (5–600 keV) localizing

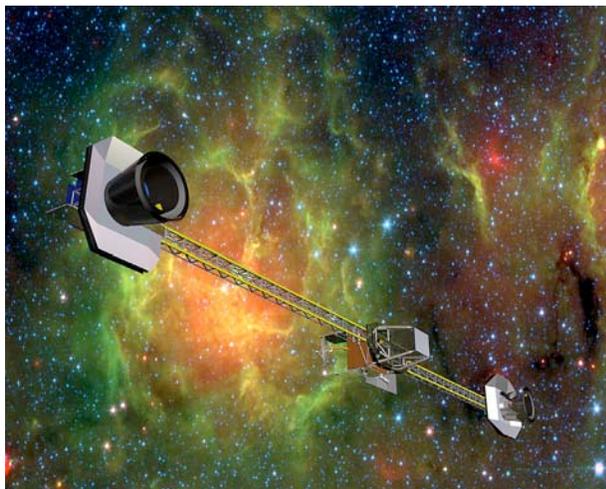
~30,000 AGN and hard-x-ray transients (Galactic and extra-galactic).

### The Space Infrared Interferometric Telescope (SPIRIT)

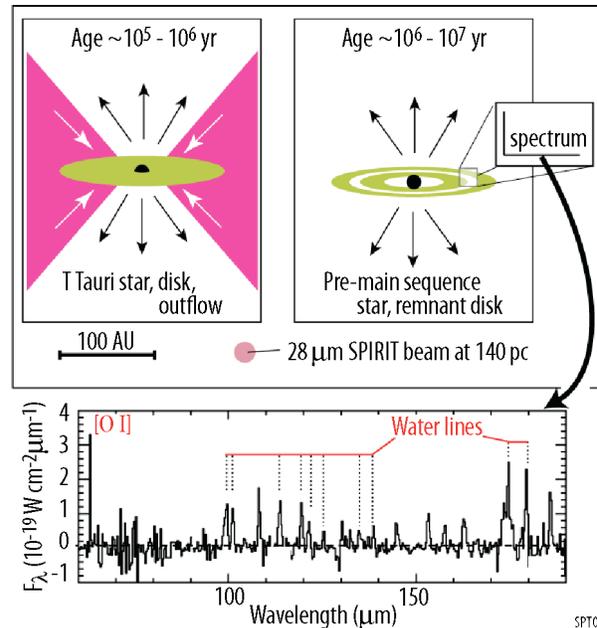
In 2004–5, with funding from NASA's Origins Probe Mission Concept Study program, Leisawitz and collaborators from ASD led a nationwide team of scientists, a Goddard-based engineering team, and four industry partners to develop a concept for the Space Infrared Interferometric Telescope (SPIRIT). SPIRIT is a two-telescope Michelson interferometer operating over the wavelength range 25 to 400  $\mu\text{m}$  and offering a powerful combination of spectroscopy ( $\lambda/\Delta\lambda \sim 3000$ ) and subarcsecond-angular-resolution imaging in a single instrument.

**SPIRIT will enable studies of astrophysical processes associated with the formation and development of galaxies and revolutionize our understanding of planetary system formation.**

With angular resolution two orders of magnitude better than that of the Spitzer Space Telescope and with comparable sensitivity, SPIRIT will provide the data needed by astrophysicists to (a) learn how planetary



SPIRIT, shown in this artist's concept, is a structurally connected far-IR interferometer for imaging and spectroscopy. Credit: NASA/GSFC



SPIRIT will map the distribution of gas and dust in young and developing planetary systems to test theoretical models and elucidate the planet formation process. SPIRIT will trace the distribution of water in its gaseous and solid states and teach us how our planet acquired its life-enabling oceans. Credit: NASA/GSFC

systems and habitable planets form; (b) find and characterize exoplanets; and (c) learn how galaxies form and change over time. SPIRIT will also take advantage of an untapped and promising realm of discovery space, enabling scientists to ask and answer questions not yet imagined.

The 2000 Decadal Survey recommended a “rational coordinated program for space optical and infrared astronomy [culminating in the assembly of] a space-based, far-infrared interferometer.” SPIRIT was explicitly recommended in the 2003 Community Plan for Far-IR/Submillimeter Space Astronomy as a practical step on the path ultimately leading to a kilometer-baseline interferometer, which will require formation flight. In response to community interests expressed in a May 2008 workshop, Leisawitz et al. (2008) described possible enhancements and estimated costs associated with extending the Origins Probe SPIRIT mission concept to a concept for a facility-class observatory. A 2009 community-based white paper titled “Far-Infrared/Submillimeter Astronomy from Space:

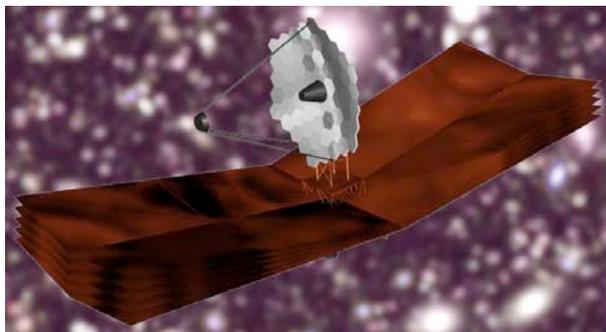
Tracking an Evolving Universe and the Emergence of Life" recommends SPIRIT for Phase A study by the end of the coming decade. SPIRIT is described in a white paper submitted to the Astro2010 Decadal Survey. The paper and additional information about SPIRIT are available at <http://astrophysics.gsfc.nasa.gov/cosmology/spirit/>,

### SAFIR Observatory

The Single Aperture Far-Infrared Observatory (SAFIR) is a concept for a large (10m class), cold (4–10 K) space telescope for wavelengths between 20  $\mu\text{m}$  and 1 mm. It will provide sensitivity that is a factor of 100 or greater than that of Spitzer and Herschel, leveraging their capabilities and building on their scientific legacies. Covering this scientifically critical wavelength regime, SAFIR will complement the expected wavelength performance of future flagship endeavors, JWST and ALMA.

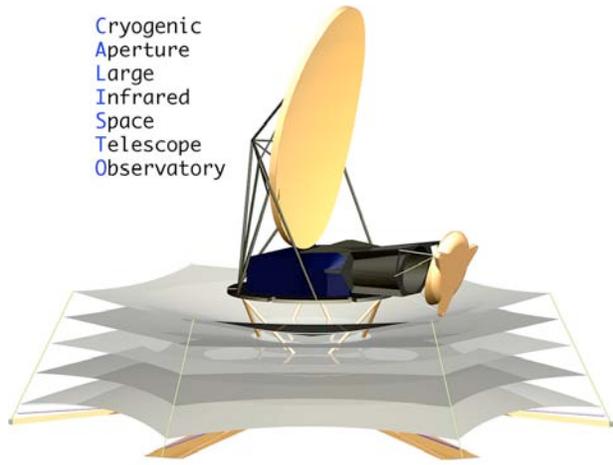
**SAFIR addresses a huge science need that is matched by promising and innovative technologies that will allow us to satisfy it.**

This Vision Mission will probe the origin of stars and galaxies in the early universe and explore the formation of solar systems around young, nearby stars. Endorsed as a priority by the National Academy of Sciences Astronomy Decadal Survey and successive NASA space science roadmaps, SAFIR addresses a



Artist's concept of the Vision Mission design for SAFIR—an 8–10m deployable telescope based on JWST technologies. Credit: NASA/GSFC

Cryogenic  
Aperture  
Large  
Infrared  
Space  
Telescope  
Observatory



A sketch of CALISTO—a 6m monolithic, off-axis mirror design that provides a downscaled but possibly more cost-effective version of SAFIR. Credit: NASA/JPL

huge science need that is matched by promising and innovative technologies that will allow us to satisfy it.

In exercising those technologies it will create the path for future infrared (IR) missions.

The key science objectives for SAFIR are:

- Probe the earliest epochs of metal enrichment and see the galaxy-forming universe before metals;
- Resolve the FIR cosmic background and trace the formation and evolution of star-forming and active galaxies since the dawn of the universe;
- Explore the connection between embedded nuclear black holes (active nuclei) and galaxy formation;
- Track the chemistry of life by measuring prebiotic molecules, ices, and minerals from clouds to nascent solar systems.
- Identify young solar systems from debris-disk structure and map the birth of planetary systems deep within obscuring envelopes.

Under the auspices of a NASA Vision Mission concept study, the SAFIR team (including ASD scientists Benford, GSFC lead, and Danchi, Leisawitz, Mather, Moseley) refined the scientific goals of the mission, ex-

explored promising approaches for its architecture, and sharpened their understanding about remaining technological challenges in order to recommend optimal strategic investments.

The results of this work have recently appeared in an AIAA volume by Marc Allen titled NASA Space Science Vision Missions. The baseline configuration is a JWST-based architecture with maximal heritage on the overall design. More recently, a downscaled but possibly more cost-effective version of SAFIR, named CALISTO, has been developed under JPL leadership. Its modest-aperture off-axis design minimizes obstructions, reduces deployments, and decreases mass, at the loss of some sensitivity and angular resolution. This may be affordable in the coming decade if endorsed by the Astro2010 Decadal Survey.

### High Energy Astrophysics Science Archival Research Center (HEASARC)

Since its inception in 1990, the HEASARC has been an essential element of NASA's astrophysics missions. The HEASARC's archive services allow scientists to identify, display, cross-correlate, download and analyze data from a variety of past and current missions including ASCA, BeppoSAX, Chandra, CGRO, Einstein, Fermi, INTEGRAL, ROSAT, RXTE, Suzaku, Swift, WMAP, and XMM-Newton and provide access to a wide range of multiwavelength sky surveys, astronomical catalogs, and other resources. The HEASARC's scientific and technical staff produces a variety of widely used software packages, provides expertise in the analysis of archived data, and helps to evolve the archive interfaces to better serve the science community.

**Papers using the HEASARC datasets comprise 10% of the total astronomical literature and include some of the most highly cited papers in the field.**

The data and software standards developed by the HEASARC provide the underlying infrastructure for the interpretation of data from a wide variety of missions. This multi-mission approach has substantially reduced the mission costs while increasing science re-

### On the Web

Cosmic Times  
cosmictimes.gsfc.nasa.gov

turn. Papers using the HEASARC datasets comprise 10% of the total astronomical literature and include some of the most highly cited papers in the field.

Since 1998 the HEASARC has enjoyed formal links with the Smithsonian Astrophysical Observatory (SAO), host of the Chandra X-ray Center, with an SAO scientist serving as HEASARC associate director. This approach integrates Chandra data into the HEASARC while recognizing the special requirements of a Great Observatory-class mission. The strong collaboration between these centers and seamless access to Chandra data from the HEASARC attest to the success of this approach. The HEASARC's SAO branch also produces and maintains important analysis capabilities, such as the immensely popular DS9 image processing and analysis package.

In June 2008, the HEASARC merged with the Legacy Archive for Microwave Background Data Analysis (LAMBDA) to better support the broad science goals of NASA's Physics of the Cosmos theme. Within the next four years, the newly combined organization (which retains the HEASARC name) will ingest observations from eight currently operating missions and up to nine upcoming missions, simultaneously serving data from these and more than 30 archival missions to the community from an archive that is projected to reach 40+ terabytes by 2012.

In 2008, NASA HQ conducted a Senior Review of NASA's astrophysics archive centers. The HEASARC was ranked joint second out of the six facilities evaluated and received a small funding augmentation to assist with the incorporation of datasets from key upcoming international missions (AGILE, MAXI, and ASTRO-SAT) and expand its efforts to develop science-based topical archives. The HEASARC is also a core partner in a recently-approved joint NSF/NASA program to manage and operate the U.S. Virtual Astronomical Observatory.

In addition to the HEASARC/LAMBDA merger and a steady stream of new software enhancements

and upgrades for the fundamental HEASoft, CalDB, XSPEC, Skyview and HERA packages, 2008 was also notable for:

- the opening of the HEASARC Fermi archive;
- release of the HEASARC Browse Notification service, which informs the user when new data are available in the archive for any specified source;
- the appointment of a new HEASARC Director (Alan Smale);
- the beginning of a major new initiative to revision and redesign HEASARC's data access and data retrieval systems. This work will continue in 2009, along with further investigation of the science-based topical archive concept and development of plans to incorporate new datasets from upcoming missions.

Funding permitting, during 2009 the HEASARC EPO program will print and distribute the Cosmic Times posters and continue to conduct Cosmic Times workshops. Cosmic Times is a curriculum-support project that traces how our understanding of the nature of the universe has changed over the past century. The project includes hardcopy posters, on-line lessons and a teacher guide, and it is largely funded by a multiyear IDEAS grant. We will also produce the 13th edition of the "Imagine the Universe!" CD-ROM — for the first time in DVD format. As in previous editions, this will contain captures of the "Imagine the Universe!" and Starchild web sites, along with the Astronomy Picture of the Day materials. The DVD-ROMs will be distributed at teacher conferences and via the NASA CORE and other relevant websites.

Looking further ahead, priorities within the 2009–2012 timeframe include the development and implementation of archives for NuSTAR, the two ground-based CMB experiments ACT and SPT, some current Explorer Program mission candidates, and the upcoming international missions; continuing support for the HEASARC's exponentially growing data holdings and retrievals; a closer integration of archive access and analysis tools; development of science-based topical archives; and enhanced interoperability with other archive centers and the Virtual Observatory, along with

a continuing effort to maintain and evolve software and data standards for new missions.

### *On the Web*

The Gamma-ray burst Coordinates Network  
[gcn.gsfc.nasa.gov](http://gcn.gsfc.nasa.gov)

In addition to the archive, the HEASARC Office (Code 660.1) also performs oversight and coordination for the Guest Observer Facilities and Science Support Centers for Fermi, INTEGRAL, RXTE, Suzaku, Swift, WMAP, and XMM-Newton. These facilities assist the astrophysics community in proposing and analyzing data from their missions and provide NASA HQ with critical organizational support for its Peer Review and program-selection activities. Some of these facilities also support mission operations, create analysis software, process data, and deliver data to the archive. Recent achievements and future expectations for these facilities are included in the sections for the respective missions.

### *Gamma-ray burst Coordinates Network*

Since 1992, ASD has operated the GRB Coordinates Network (GCN). The GCN distributes positions, light curves, images, and spectra on gamma-ray bursts and other gamma-ray transients in real time collected from five active missions to over 600 recipient sites (telescopes, missions, observers, etc.). These GCN Notices enable rapid follow-up observations.

Notices are distributed using a combination of Internet socket and email-based methods. Through GCN Circulars and Reports, the network also collects and distributes worldwide the results of follow-up observations made by the recipients of GCN Notices.

## VI. Education and Public Outreach in NASA's Astrophysics Science Division

The Astrophysics Science Division (ASD) supports a strong and vibrant Education and Public Outreach (EPO) program. The EPO team includes members who support various NASA astrophysics missions and programs, including ACE, Beyond Einstein, HEASARC, Integral, JWST, Suzaku, and RXTE. The team also supports a broader EPO effort that is not mission specific and covers ASD science and technology.

There are several notable EPO efforts in ASD serving a diverse range of audiences. We have developed a wide variety of curriculum support materials for teachers over the years. One such ongoing effort is the “Cosmic Times” project, which presents the history of our understanding of the nature of the universe through the 20th and early 21st century. The series traces this history from the confirmation in 1919 of Einstein’s theory of gravity, to Hubble’s discovery of the expanding universe, the development and evidence for the Big Bang, and finally the discovery of dark energy. Additional curriculum support materials developed over the years are available to educators through our “Imagine the Universe!” website.

In 2007–2008, the ASD also ran a year-long education program for high-school physics teachers called the Beyond Einstein Teachers’ Academy (BETA). The



Every month, the Goddard Visitor Center hosts the NASA Family Science Night program. Credit: NASA/GSFC.

goal of this program is to educate teachers about cutting-edge research and have them design projects to incorporate the science into their high school physics classes. The 2007–2008 BETA focused on the topic of black holes and strong gravity and was highly successful.

**The EPO group’s continuing efforts bring the “Universe Down to Earth.” In 2009, major new programs will support the International Year of Astronomy.**

Several programs and efforts target audiences in out-of-schooltime settings. Afterschool Universe, an afterschool astronomy program, introduces middle-school children to the universe beyond the solar system. This program was launched nationally in 2008 and has been received with great enthusiasm by the afterschool community all across the country. More than 150 afterschool program leaders were trained to deliver this program in 2008 and the list of partnerships and implementers steadily grows.

The Family Science Night (FSN) program works with families and their middle-school children to engage them in science. FSN is offered monthly at the Goddard Visitors’ Center and is a joint effort between the Astrophysics and Heliophysics Divisions at Goddard. It is an extremely popular program with the local community and received a Goddard Honor Award in 2008. This program will be expanded to be nationwide in 2009.

The Big Explosions and Strong Gravity (BESG) program targets Girl Scouts aged 11 to 13. This is a one-day event where girls meet real scientists and join them for a day of hands-on exploration into supernovae and black holes. Girls whose interest in science is piqued by this event can participate in a follow-on program, the A.C.E. of Space club (A.C.E. stands for Astronomical Cosmic Exploration). This is a girl-led club and the members explore different parts of the universe during their meetings over the course of a year.

The ASD EPO group has also been active with developing museum displays and exhibits. The group developed a display for the Goddard Visitors’ Center



High school physics teachers learned about black holes and strong gravity in the Beyond Einstein Teachers' Academy in July 2007. Four follow-up meetings were held during the 2007–2008 school year. Credit: NASA/GSFC.

in 2007 highlighting the science and technology programs in the Division. We also developed a traveling exhibit for the James Webb Space Telescope in 2008, as an add-on to the highly popular Hubble Space Telescope traveling exhibit. This exhibit will travel to three locations in 2009.

In addition, the ASD also has a dynamic online presence and a growing new media effort. We have several popular sites targeted at the public and educators. These include StarChild, Cosmicopia and Imagine the Universe! The ASD EPO group produced a set of podcasts in 2007 titled “Blueshift.” A new media effort that includes podcasts and blogs has been launched in 2009 in support of the International Year of Astronomy.

For JWST, we launched a major online outreach effort in 2008. We developed an online Flash game to teach the visitor about modern telescopes such as Hubble and JWST and their commonalities and differences with traditional telescopes. We also ventured into SecondLife and established a presence on Facebook that has been extremely popular. Finally, we developed an online interactive version of the JWST traveling exhibit to reach the public that will not be able to travel to the exhibit locations.

The ASD EPO group was a major participant in several high-profile outreach efforts in 2008. NASA was

*On the Web*

- ASD EPO**  
[astrophysics.gsfc.nasa.gov/outreach/](http://astrophysics.gsfc.nasa.gov/outreach/)
- Afterschool Universe**  
[universe.nasa.gov/afterschool/](http://universe.nasa.gov/afterschool/)
- Beyond Einstein Teachers' Academy**  
[beyondeinstein.nasa.gov/education/beta.html](http://beyondeinstein.nasa.gov/education/beta.html)
- Big Explosions and Strong Gravity**  
[bigexplosions.gsfc.nasa.gov](http://bigexplosions.gsfc.nasa.gov)
- Blueshift**  
[universe.nasa.gov/blueshift/](http://universe.nasa.gov/blueshift/)
- Cosmic Times**  
[cosmictimes.gsfc.nasa.gov](http://cosmictimes.gsfc.nasa.gov)
- Cosmicopia**  
[helios.gsfc.nasa.gov](http://helios.gsfc.nasa.gov)
- Family Science Night**  
[sdo.gsfc.nasa.gov/epo/families/fsn.php](http://sdo.gsfc.nasa.gov/epo/families/fsn.php)
- Imagine the Universe!**  
[imagine.gsfc.nasa.gov](http://imagine.gsfc.nasa.gov)
- James Webb Space Telescope**  
[www.jwst.nasa.gov](http://www.jwst.nasa.gov)
- StarChild**  
[starchild.gsfc.nasa.gov](http://starchild.gsfc.nasa.gov)

one of the featured groups at the Smithsonian Folklife Festival in 2008. The ASD EPO group played a major role in organizing the representation of Astrophysics at NASA. Similarly, we played a key role in LaunchFest, the Goddard Open House held in Sept. 2008.

The group continues its efforts to bring the “Universe Down to Earth” with its ongoing efforts as well as major new efforts planned in support of the International Year of Astronomy in 2009.